SAND 79-0637 UNLIMITED RELEASE PRINTED JUNE 1979

SYSTEMS INTEGRATION AND FNGINEERING SUPPORT STUDY FOR THE STRATEGIC PFTROLEUM RESERVE (SPR) PROGRAM

FINAL REPORT

ABSTRACT

Based on a request by DOE Under Secretary Dale Myers, Sandia Laboratories, with the assistance of the Corps of Engineers, undertook a short-term systems integration and engineering support study for the Strategic Petroleum Reserve (SPR) program. This overview study was initiated December 1, 1978, and concluded March 31, 1979.

The objectives of the study were to:

- 1. Assess and evaluate the assumptions and criteria upon which the SPR program was established,
- 2. Identify potential technical problem areas,
- 3. Recommend R&D programs to address identified technical problems,
- 4. Assess the capabilities of the Early Storage Reserve (ESR) system,
- 5. Assess the capabilities of the proposed SPR system, and
- 6. Provide preliminary recommendations on systems engineering management needed to accomplish program objectives.

This report describes the study effort and provides conclusions and recommendations in each area.

ACKNOWLEDGEMENTS

The cooperation of the SPR Program Office (Washington), the SPR Project Management Office (New Orleans), and the SPR contractors management and staff is acknowledged. It is hoped that the assessments, conclusions, and recommendations contained in this report are of assistance to the SPR program management in their efforts to develop and implement this program.

The principal investigators and contributors to this study are listed in Appendix A. Their efforts in the conduct of this study and in the preparation of this report are also acknowledged.

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I. INTRODUCTION

Sandia Laboratories was requested by DOE Under Secretary Dale Myers to perform a short-term systems integration and engineering support study for the Strategic Petroleum Reserve (SPR) program. 'Ine study was initiated December 1, 1978 and concluded March 31, 1379.

It was recognized at the start of this study that the SP!? was a large and complex program dedicated to storing a large quantity of crude oil on an extremely ambitious time schedule. Because of the short duration of this study, its focus is not on accomplishments or areas where it was felt that technical risks were minimal. Rather, the emphasis has been on an assessment of potential risks existing in the program and recommendations of programs to understand and reduce them.

'The Turnkey approach to achieve the last increment of the SPS storage has not been analyzed in this study. Therefore, no endorsement nor rejection of this approach is offered.

'The objectives of the study, as specified by the SPF Program manager were to:

- 1) Assess and evaluate the assumptions and criteria upon which the SPR program was established,
- 2) Identify potential technical problem areas,
- 3) Recommend R&D programs to address identified technical problems,
- 4) Assess the capabilities of the Early Storage Reserve (ESR) system,
- Assess the capabilities of the proposed SPR system, and
- 6) Provide preliminary recommendations on systems engineering management needed to accompl ish program objectives.

To conduct this study, a multidisciplined team of Sandia Laboratories and Corps of Engineers personnel (Appendix A) was assembled. The members of this team held numerous discussions with SPR personnel, reviewed reports and drawings (Appendix P) and held in-depth discussions with all major contractors involved in the SPR program (Appendix I?).

Detailed studies and analyses were Performed in a number of areas and are included in the Technical Appendices section of this report.

Following is a synopsis of the major investigations, conclusions, and recommendations. Some additional technical recommendations are contained in the Technical Appendices section,

II. PROGRAM ASSUMPTIONS AND CRITERIA

An assessment of the program assumptions and criteria includes examining the decisions leading to a specific SPR system definition, The major steps that lead to a system definition have been reviewed.

A) Interruption Scenarios and Shortfall Analyses

The first step, definition of a range of oil supply interruption scenarios, was performed by the DOE Office of International Affairs and has been approved by the National Security Council. Three scenarios and their impacts are currently being considered by SPR, but the principle design scenario is a 50% OAPEC (Organization of Arab Petroleum Exporting Countries) embargo aimed at the US with a duration of nine months.

The supply interruption scenarios have been translated into daily and integrated petroleum shortfalls by oil type. Factors considered in these analyses were projections of US oil import levels, projections of producing countries' oil export levels by oil type, and consideration of international agreements, such as the International Energy Plan. These analyses have been performed by the DOE International Energy Analysis Division and are part of an ongoing effort to understand the international energy system.

The oil supply interruption scenarios and the subsequent oil shortfall analyses are adequate for SPR design definition.

B) Determination of Reserve Size and Drawdown Rates

The second step is the determination of reserve size and maximum SPR drawdown rate by oil type. These criteria are not currently fixed and they should be established prior to final SPR configuration. Purely auantitative calculations of the reserve size and drawdown rate are not feasible because of the influence of such factors as the probability of an oil supply interruption, its economic impact and national security implications. Congress has currently authorized a 750 million barrel (MMB) reserve, but expansion to a 1300 MMB reserve is under consideration.

Both criteria are required to perform a distribution system analysis. As the quantity of stored oil and the specified drawdown rate increases, the demands on the external distribution system also increase. An SPR system configuration that is designed to distribute 750 MMB of oil at a maximum rate of 4.5 MMBPD (million barrels per day) and is then incrementally changed to 1000 MMB of oil and a rate of 6.0 MMBPD, may not have the same configuration as a system originally designed as a 1000 MMB reserve.

The lack of drawdown criteria also leads to specific site design problems. In the original Early Storage Reserve (ESR) plan, the sites were required to be able to withdraw all of the oil in 150 days. The DOE Office of Emergency Response Planning states that this criterion is no longer valid. Since the 150 day criterion was the last stated drawdown criterion, it is still being used by the SPR Project Management Office for the expansion phase site design.

The reserve size and especially its drawdown rate are two basic criteria required for SPR design and must be established.

C) Demand Requirements/Distribution System Analysis

Efforts have been initiated by the SPR Program Office to determine crude-oil demand requirements (type, location, quantity) and the interrelationship of the SPR system with the national petroleum distribution system (i.e., terminals, ports, pipelines, refinery complexes). These studies have not progressed sufficiently to allow evaluation. Determination of these requirements have an influence on SPR complex designs, locations, and interconnects with the national distribution system. This distribution system analysis will influence turnkey site selection.

Pricing and allocation policies for the SPR system will also influence SPR crude-oil demand requirements and should be considered.

D) Salt Cavern Storage

Solution mined salt caverns and an excavated salt mine along the Gulf Coast have been chosen for storing the first several hundred million barrels of oil. This decision still appears to be the most cost-effective choice for long-term storage of oil in huge quantities, Their proximity to major terminals, pipelines and refinery complexes also contributes to the validity of their selection.

However, the extent to which this conclusion remains true depends on the study of the petroleum distribution system. It is possible that the results of the analysis may dictate that some increment of the reserve should not be located on the Gulf Coast. If so, salt domes may not be available and alternate storage methods may have to be developed.

III. ASSESSMENT OF TECHNICAL PROBLEMS

The SPR Program was explored for potential technical problems in the following areas: a) geological/site characterization, b) long-term cavern/mine geomechanical stability, c) brine disposal, d) three-well leach/fill process, e) material corrosion, f) fluid circulation in caverns, and g) long-term crude-oil physical/chemical stability. Programs to understand and solve identifiable problems are outlined.

A) Geological/Site Characterization

A basic understanding of the geology associated with the salt formations utilized for storage and adequate site geological characterization are needed to: 1) assess geomechanical stability of existing caverns and mines, 2) characterize reservoirs for brine disposal, 3) develop new storage caverns, 4) provide information needed to monitor the long-term state-of-health of the storage sites and the stored products, and 5) provide baseline information which could be needed to effectively respond to emergency situations.

Discussions with DOE/SPR program and project personnel, Fenix and Scisson, PB/KBB, and Louis Records were held to assess and determine the state of geologic information on the SPR sites. Additionally, geotechnical reports available to SPR were reviewed to determine what geological studies had been completed at the various sites. An annotated bibliography based on this review is contained in Appendix Q. In addition, a detailed assessment of the requirements for, and the status of, geological/site characterization efforts for the Bryan Mound site was undertaken as a representative case.

While it is difficult to quantitatively justify the amount of site specific geological studies that should be undertaken in support of the SPR program, it is noted that the financial investment in all sites, facilities as well as stored crude oil, is immense and prudence dictates that a small percentage of the total site investment be expended to better characterize the site geologically.

The following assessments have been made:

1) Although some geological studies have been completed for the Bryan Mound, West Hackberry, and Sulphur Mine sites there still exists a need for additional geological studies at these sites. The best overall geological descriptions available today for these sites are contained in the original FEA feasibility studies. These studies were conducted at a feasibility level and additional geological investigations were presumed.

- 2) The available geological studies for the Bayou Choctaw site are more comprehensive. However, these studies confirmed that cavern #20 is close to the edge of the dome and recommended that additional surveys be conducted prior to oil fill. These surveys have not yet been conducted.
- 3) Most subsequent geological investigations have been problem-specific, (e.g., brine disposal, inputs for environmental statements, etc.) and are insufficient with respect to providing a comprehensive geologic understanding.

The site specific study of Bryan Mound noted that geotechnical concerns have already arisen because of geological unknowns. The two major concerns are the unstable fluid conditions in cavern #3 and the anomalous zone of highly insoluble material in cavern #5. Lack of precise data on cavern and dome dimensions, noted in the next section, may also have an impact on understanding long-term cavern stability.

It is recommended that:

- A geoscience capability be established within the SPR organization to conduct and/or direct long-term geological, geophysical, and hydrological studies and to assist in solution of geotechnical problems,
- 2) A central file of geological reports should be established within the program: personnel responsible for the sites should have increased familiarity with all the geologic data that do exist,
- 3) A sufficiently comprehensive site geological plan be developed and implemented to provide the necessary site specific data base to better support the planning, design, construction, and operation of crude-oil storage facilities, and
- 4) It is our understanding that a geological and geotechnical evaluation is required with each turnkey proposal; however, because of the high cost, an in-depth evaluation cannot be provided at the proposal stage. Contracts for selected sites should include adequate provisions for geological assessments which should be completed before initiation of major construction and oil storage.

The recommended SPR site geological characterization plan should be divided into two phases. The initial phase should consist of the compilation and consistent interpretation of existing data. The results of this effort would be:

- 1) The development of a site specific geological setting,
- 2) Early identification of anomalies which may indicate problems, and
- 3) An outline of areas, if any exist, that need additional study, a rank order of the problems, recommendations of approaches to resolve the problems, an estimato of resources required, and potential payoff from the conduct of these studies.

The second phase would consist of test drilling and obtaining and interpreting new surveys to supplement geological data not available in the first phase, and to verify data and subsequent conclusions from the first phase. Examples of expected activities include drilling to verify the condition of the caprock, drilling and logging of slim holes preceding final selection of locations for new caverns, geophysical surveys, ground water studies, etc. The extent of phase two can only be determined after a thorough evaluation and review of the results and recommendations from phase one.

B) Long-Term Cavern/Mine Geomechanical Stability

It is essential to assure the long-term stability of SPR caverns or mines so that serious failures will not occur which could cause severe environmental impacts, economic losses, or failure to withdraw oil. The ESR phase utilizes existing caverns with shapes and spacing significantly different from those designed for hydrocarbon storage. This observation should not imply that these caverns are unsuitable for crude-oil storage. Rather, it should indicate that if existing caverns are to be used, additional engineering studies and testing should be performed. The expansion phase caverns also require comprehensive geomechanical studies to ensure long-term stability because of the size of these new caverns, their depths and lack of information regarding site specific salt properties.

This assessment of geomechanical stability of the SPR caverns and mines is based upon detailed discussions with SPR project personnel and contractors, evaluation of the SFR-sponsored work recorted to date, comparison of the SPR program with other industrial and governmental storage programs, and Sandia-conducted salt properties measurements in the laboratory and numerical simulations performed during the course of this study.

Cavern Stability - Representative of efforts by SPR contractors to date to address cavern geomechanical aspects are the cavern certification program; a preliminary cavern stability assessment at the four ESR sites; and a site-specific study of salt dome geology and stability of the caverns at the Bayou Choctaw site.

While the past geomechanical investigations for the SPR program were thorough and adequate in many areas, the existing SPR-sponsored studies and this evaluative study have defined areas in which additional investigations are recommended for future cavern selection and certification (additional efforts could lead to more useful cycles for certain caverns) and for cavern operations (establishing cavity closure rates, depressurization effects, and failure criteria).

The basic recommendation offered in this evaluation is that final design of the new caverns and evaluation of the existing storage caverns should parallel an expanded geomechanical investigation that addresses site-specific questions. Cavern-specific recommendations (additional recommendations are provided in Appendix F) are:

- 1) At the Bryan Mound site, additional studies are recommended to assess in greater detail: a) the potential impact of cavern #3 (not a storage cavern) on the storage caverns (a plan has been developed by SPR but not implemented), b) the effects of depressurization on the casing seat in cavern #2 (casing seat is at the top of this cavern), and c) the possible effects on cavern integrity of a postulated insoluble stringer in cavern #5,
- 2) At West Hackberry, an assessment of cavern #6 depressurization effects should be pursued through: a) additional geomechanical modeling efforts, b) the monitoring planned in the cavern reentry program, and c) the ensuing cavern surveys. Cavern #11 offers a unique opportunity for prototype studies of the proposed new cavities since it is geometrically similar and is well isolated from dome boundaries and other caverns,
- 3) At the Sulphur Mines site, because of a variance in estimates regarding location of the edge of the dome relative to caverns #6 and #7 it is recommended that edge-of-dome investigations be completed prior to crude-oil storage, and
- 4) The most complete geotechnical studies in the SPR program have been made for the Bayou Choctaw site. The highest priority of the existing cavern stability recommendations is to ensure that caverns #15 (ESR cavern) and #17 (Allied-owned cavern containing ethane) can be compatibly operated. It would be desirable to have SPR purchase cavern #17 or obtain a satisfactory working agreement with the present operators (being pursued by SPR).

A comparison of the SPH design for expansion caverns with other similar storage projects was conducted. The comparison reveals that none of the other crude-oil storage facilities have been constructed at the same depth and spacing as planned for the SPR caverns (the German caverns are at the same depth but have a much greater spacing while the LOOP complex will use a similar spacing but are at only 1/2 the depth of the SPR caverns). Creep analyses for the SPR caverns (by University of Illinois for PB/KBB) indicate that only minimal closure would occur in the SPR caverns while a more detailed study for LOOP caverns (by Serata Geomechanics, Inc. for LOOP) indicates that large amounts (greater than 10%) of closure might occur.

In view of the above differences, a more thorough assessment of the impacts of planned spacing of SPR expansion caverns is warranted in order that operations can be planned accordingly.

<u>Programmatic recommendations for the SPR geomechanics efforts</u> include the <u>development of a closely coordinated program</u> (including program definition documents) devoted to coupling the laboratory and bench-scale studies, the numerical simulation efforts, and the results of judiciously selected field tests to increase confidence in the overall design approach. This effort should include:

- 1) The development and implementation of a testing program for obtaining site-specific material properties for each site, (Tests should concentrate on the evaluation of a single site. For additional sites, test matrices should be designed to index the salt properties relative to the well-characterized site).
- 2) Creep studies using temperature-dependent, site specific material properties to determine long-term (steady) creep rates of the caverns to allow more detailed assessment of cavern spacing ratios,
- 3) A thorough assessment of the potential impacts (and probability of occurrence) of slabbing of the spire material, a result of the multi-well leaching concept, during dissolutioning on the usability of the nearby brine strings,
- Performing bore hole deformation caliper surveys of the cavern well holes prior to the initiation of leaching, and
- 5) Study downhole or intracavern instrumentation systems such as borehole acoustic probes for monitoring cavern stability and for evaluating cavern shapes to determine if applicable and cost-effective monitoring systems can be developed.

Weeks Island Mine - The existing room and pillar salt mine is being converted for oil storage. Plans include a provision to develop a new commerical salt mine beneath (or adjacent to) the converted mine. Two structural stability concerns have previously been raised:

- 1) Adequate separation between the oil reservoirs and the proposed new mine, and
- The control of a water leak developed during mining carried out as part of the conversion plan.

An independent analysis performed by Sandia supports the design proposal of a 300-foot web thickness (separation) developed by Acres American, subcontractor to Gulf Interstate for SPR. The Acres American report did not address one concern regarding that proposal and recommended future work--the consequences of possible outbursts associated with the new mining on the structural integrity of the web. Such an effort has been carried out by Dames and Moore for Morton Salt. Specific mining approaches are recommended by Dames and Moore to minimize the likelihood of outbursting. The numerical simulations performed by Sandia indicate that an outburst (40 feet in diameter and 150 feet in height, which is larger than previously observed during the original mining at this site) does not substantially reduce the integrity of the web and that establishing communication between the new mine and the existing mine by outbursting is unlikely. The conclusion is that the present geomechanical design for the oil reservoir/new mine appears to be structurally adequate.

Work on control of the water leak by Morton Salt, its subcontractor Dravo, and Parsons and Gilbane has been reviewed, including a site visit. The problem is being properly addressed.

C) Brine Disposal

The brine-disposal well system was designed based on average well capacities of 30 MBPD (thousand barrels per day) which corresponded to the maximum rate historically achieved in the Gulf Coast region. This value was ascertained from FEA feasibility studies which relied on limited geological information and limited performance data from wells at or near the anticipated SPR sites. Actual performance of SPR wells has been less than 50% of the predicted capacity.

The problems encountered with brine disposal are a result of:

- 1) an initial overestimation of the average well system capacity,
- 2) improper well completion and clean-out techniques and 3) a lack of implementation of proper monitoring, test, and maintenance of the brine-disposal system.

These deficiencies have been recognized by the SPR Project Office, and appropriate action is being taken to correct them, If the planned improvements and recommendations proposed by the Brine Disposal Task Force are implemented, significant improvements in brine-disposal capacity will be realized. Even with the improvements, however, the desired capacity may not be achieved with existing wells because of the initial overestimation of well capacities,

A properly deaigned, functional, brine-disposal system (especially a well system) will require constant technical attention, monitoring, and ma intenance. Concerns in this respect prompt the following recommendations:

- Maintain a functional disposal well system as a backup to the pipelines Co the Gulf at Bryan Mound, West Hackberry, and any future site where both capabilities exist,
- 2) Since the disposal wells and the pipelines will be left shut in and static over a period of years, initiate a study to determine procedures for assuring that the brine-disposal system will still be functional when required for refill, and
- Maintain adequate well instrumentation, i.e., pressure and flow data, for evaluating and predicting well perfor mance.

The design and specifications for the brine-disposal pipeline to the Gulf, including the diffuser and the environmental monitoring plan, have been reviewed and are considered technically adequate except for the following:

- 1) The EPA permit currently allows the discharge of 680 MBPD of brine into the Gulf, which is less than the capacity of the pipeline and diffuser (1000 MBPD). The time urgency of oil storage, and dollar savings associated with increased brine disposal rates provide an incentive to modify the EPA permit to allow disposal of brine at a rate equal to the maximum capacity of the system,
- 2) Current plans call. for manual opening and closing of the diffuser nozzle valves by divers to maintain an optimum nozzle discharge velocity. The sensitivity of environmental impact due to brine diffusion in the gulf to the nozzle discharge velocity should be examined further with the objective of eliminating manual control operations,
- 3) A tremendous quantity of data have been and will continue to be collected as part of the environmental monitor ing plan. The usefulness of the data in determining

any adverse effects, and the success of the monitoring program in satisfying EPA requirements depend upon the design and implementation of a data synthesis and analysis program and the establishment of parameter baselines so that significant deviations can be readily observed. It is recommended that this effort be initiated immediately. (Efforts have been initiated by SPR.)

D) Three-Well Leach/Fill Concept

The three-well leach/fill concept involves simultaneous leaching and oil filling through three equally spaced wells to form three caverns which coalesce to form a single cavern as leaching progresses.

The original impetus for the three-well per cavern concept and the simultaneous leach/fill of several caverns was to achieve maximum oil storage in the shortest time. Although studies still indicate that this concept offers accelerated oil storage compared to a single-well leaching approach, it is a new, untried process involving greater risk and potentially greater cost (dependent on future oil prices). The added risk is associated principally with:

- 1) Possible damage to the suspended casings and/or brine strings from a falling mass of salt during leaching,
- 2) The requirement that three wells, rather than one, be operable all of the time for leaching (cavern formation) to progress in a controlled manner, and
- 3) Cavern growth and leaching time that was predicted from a numerical model that has not been validated for the three-well concept.

Delays in the three-well leaching program might be caused by:

- 1) A single well failure,
- 2) Delayed leaching in one or two wells per cavern to maintain symmetry in the three caverns,
- 3) Downtime to replace damaged casings or brine strings, and
- 4) Downtime to conduct sonar surveys more frequently than planned to aid in control of leaching.

Unplanned delays may also develop because of the complexity of intermittent oil injection requirements associated with the three-well process and a resulting inability to supply

adequate oil from **onsite** storage at times, SPR has developed an oil fill schedule which meets the injection requirements and which results in a nearly **constant** site oil delivery rate. However, this plan is based on projected three-well leach schedules.

Significant cost saving for new cavern development under a large, single-well plan compared to the three-well plan were estimated (from reports prepared by PB/KBB and DUCI) for Bryan Mound and West Hackberry combined,

The increase in crude ail **stored** during new cavern development for the three-well plan as compared to a single-well plan (PB/KBB report) is shown below.

	Bryan <u>Mound</u>			West Hackberry		
	Three- Well (MMB)	Single Well (MMB)	Difference (MMB)	Three- Well (MMB)	Single- Well (MMB)	Difference (MMB)
1982	36	61	+1	34	30	t 4
1983	92		+3	74	65	+.9
1384	120,	a8	+4	115	102	+13
1985	•	114	+6	155	138	+17
1986	120	120	+0	160	160	+0

From a Current program view, the gains in the oil-fill schedule appear small compared to the increased cost and risk for the three-well concept.

At this date (the cavern wells are being drilled at Bryan Mound), a change in plans might cause undesirable delays in the program; the concerns and doubts expressed above may not justify such delays. However, the question of using a single-well leaching concept should be reexamined in light of the revised schedule and storage goals. In any case, it would be prudent to have a backup plan, ready for implementation. Actions to study this issue are continuing.

The following actions are therefore recommended:

- 1) Reconsider the use of the single well leaching method for new cavern creation,
- 2) Develop an alternate (backup) expansion plan based on a single-well leaching process which can be implemented if significant problems' develop with the three-well plan, and
- 3) Because the original simulation model is proprietary, determine as soon as possible if the computer model being used by the current contractor can be modified to accurately simulate the three-well process.

Investigate the feasibility of laboratory simulation testing to validate the model. A full-scale validation test can be conducted on the first three-well cavern to be leached at Bryan Mound.

E) Material Corrosion

An important technical consideration for the viability and reliability of the SPR program is the compatibility of system components with corrosive environments. This problem was recognized early by the SPR Program/ Project Office and the system designs incorporated features such as cathodic protection, coatings, and double casings.

To assess whether all potential corrosion problems were recognized and addressed adequately, a complete analysis was made using suitable electrochemical corrosion principles on the basis of general conditions. at various sites. This was followed by specific site investigations. The two major potential problem areas identified are:

- Corrosion of exterior well casings by acidic groundwaters which contain dissolved sulfur species in the caprock, and
- 2) Corrosion of brine pipes by brines containing dissolved oxygen.

Based on the analysis and laboratory examination of corroded pipes, it is concluded/recommended that:

- 1) The use of double casings and cementing as currently planned probably represents the best method of minimizing corrosion due to acidic water in the caprock. Analyses of deep groundwaters have not been made but should be, to aid in predicting expected life of casings, and
- 2) While concentrated brines that are free of oxygen do not represent a major corrosion problem, using uncovered brine ponds and fresh water for leaching will introduce oxygen. Tests performed for SPR of aerated brines show that unacceptably high corrosion rates can be reduced to tolerable levels by the use of SO₂ to deoxygenate the brine. However, the possible reduction of sulfates by anaerobic sulfate-reducing bacteria may lead to even more severe corrosion. No SO₂ injection is recommended unless suitable tests refute the sulfide corrosion problem.

F) Fluid Circulation in Caverns

The fluid circulation field in a cavern is of interest because, 1) the homogenity and stability of the crude oil is influenced by the mixing rate, and 2) the circulation fields arising when

there is fluid flow into or **out** of the cavern **can** potentially exert considerable local force on the piping. The cause **of a** problem with the brine string in cavern #5 at Bryan Mound was suspected to be a **circulation-induced** drag force. Preliminary analysis based on a free-vortex model indicated that high stresses could be induced in the brine string, but a more detailed analysis including **momentum** and energy losses reveals that this <u>was not</u> the **cause** of the problem. An oil flow rate an order of magnitude higher than the SPR design value **would** be required to **cause** stresses capable of damaging the pipe.

No further evaluation of the brine string fluid circulation problem is needed. It is recommended that fluid circulation analysis to address oil stratification concerns be conducted.

G) Long-Term Crude-Oil Physical/Chemical Stability

In order for SPR to be effective, the recovery and refining quality of the stored crude oil must be guaranteed. The history af storage of crude oil and petroleum distillates in salt/brine environnenta is short, and as a result, little information is available regarding the physical and chemical properties of crude oil after prolonged storage although no immediate problems are anticipated.

SPR Program Office, through KBB and the Bartlesville Energy Technology Center (BETC), are addressing the question of the physical and chemical stability of crude oil in solution-mined caverns (brine/salt interfaces) by a sampling/analysis program involving German storage caverns, Etzel K-117, Lesun L-103 and Lesum L-104. A comparable pragram does not exist for the Weeks Island mine (inert atmosphere/salt interfaces). No current program studies biodeqsation of crude oil in either solution-mined caverns or salt mines, Current SFR procedures sample procured crude oil at the point of tanker offloading; no sampling program for crude oil in storage is presently 'conducted.

Occurrence of a heavy viscous petroleum phase at the crude-oil/brine interface at Etzel cavern K-117 and Lesum L-103 by the above mentioned sampling program emphasizes the need for an ongoing crude-oil quality assurance program. We have ascertained that this viscous phase was caused by a concentration of paraffinic waxes; whether this concentration, some 1-3m thick, represents a continuing chemical process is unknown. Contained within the caverns, this viscous layer may not present any problems. At the Weeks Island mine, formation of this viscous layer could pose withdrawal difficulties since the 'crude oil is pumped via submersible pumps from the bottom" where the higher gravity waxy phase will settle. In both cases, if the waxy fluid is withdrawn, severe pumping and piping problems could result.

Other crude-oil stability concerns include: potential interaction exists between bacteria and the stored crude

oil (biodegradation): stratification of crude oil may occur presenting some refining problems: and commingling of different SPR designated type crude oils (has occurred in limited instances) may affect stability.

While the sampling/analysis studies of KBB and BETC are a significant step in assessing long-term stability, we recommend that surveillance of the U.S. stored crude oil should be conducted: 1) to establish an adequate reference data base if additional studies are needed; and 2) to ensure that no surprises are occurring.

Specifically, we recommend, although no immediate problems are indicated, that the current sampling and analysis program should be expanded to include:

- The quantity of each type of crude oil being stored in each cavern and mine should be recorded and sampled. The crude-oil sample should be analyzed so the physical/ chemical nature at the time of storage is known,
- 2) The crude oil in each cavern and mine should **be** sampled periodically so that the physical/chemical state of the stored crude oil is known,
- 3) Aerobic sampling of crude oil at the crude-oil/vapor interface at Weeks Island Mine, and anaerobic sampling of crude oil and brine at the crude-oil/brine interface in solution-mined caverns with subsequent bacteria culture development should be initiated to determine if hydrocarbon biodegradation is occurring, and
- 4) The extent of stratification of crude oil in each cavern should be determined to adequately inform petroleum refiners of the expected type of crude oil.

Further recommendations for crude-oil quality assurance include:

- 1) DOE-designated crude-oil types should be segregated in storage, and
- 2) Continued surveillance of purchased crude oil should be conducted to ensure specifications are being met with respect to compatibility with site equipment.

IV. ASSESSMENT OF CAPABILITIES OF THE ESR/SPR SUBSYSTEMS

Detailed **assessments** of selected subsystems at the Bryan Mound site have been undertaken. The results from these assessments are assumed to be indicative of the **status** of other **subsystems** at the Bryan Mound site and of other ESR sites in general. **Subsystems** selected (by Sandia and SPR Project Management Office) include: 1) site pump/pipeline withdrawal capability, 2) the

electrical power subsystem, 3) the pump-motor subsystem, 4) the site instrumentation and control system, and 5) the long-term monitoring of "state-of-health" of the site capabilities and its stored oil. All comments are relative to site designs as of January 1, 1979. The conclusion reached in this assessment is that the site system designs when completed are, in general, adequate for fill, withdrawal, and refill.

A) Site Withdrawal Analysis

To assess the withdrawal capabilities of the ESR/SPR design, a detailed analytical network model of Bryan Mound was completed. A limited look at the other sites indicates that, similar to Bryan Mound, the designed withdrawal hardware will have adequate capacity when installed. Detailed analyses similar to the Bryan Mound analysis will be necessary to determine if specific design deficiencies exist. Specific comments on the ESR and SPR withdrawal capabilities are presented below.

Since conventional mines represent a different type of withdrawal system, specific comments on the Weeks Island Mine are included.

Bryan Mound ESR Capabilities - The analysis indicates that adequate pump capacity is available but two concerns have been indentified:

- 1) The ESR raw-water injection pumps result in large pressure drops across all cavern raw water flow control valves. According to one valve manufacturer, such pressure drops will cause the valves to operate in the cavitation region with a very short useful life (hours). Upon completion of the expansion phase this problem will be eliminated since a different set of pumps will be used for water injection, and
- 2) At the maximum withdrawal rate, the crude-oil velocity can cause pitting and material loss from the interior walls of the crude-oil pipes from wells 1A and 5A.

Bryan Mound SPR Capabilities - Using the same assumptions as in the ESR case, an assessment of the expansion capabilities was conducted and the following results noted:

1) The wells, pumps, and piping up to the oil-injection pumps are adequate to support a 1.02 MMBPD flowrate. In fact, these elements wauld allow for a 1.4 MMBPD withdrawal rate out of the expansion caverns assuming one type of oil in all new caverns. The onsite sys tern, however, is limited by the 30 in. pipe between the oil-injection pumps and metering station to a site flow of 950 MBPD.

- 2) Although not a part of the withdrawal network, it was noted that the combination of injection and booster pumps in series is adequate to supply the flow and pressures required for planned leaching operations, and
- 3) Due to design limitations which prohibit simultaneous pumping of more than one type crude oil offsite, the 150 day withdrawal criteria cannot be met due to the projected sweet/sour mixtures. This problem is documented and well understood by the concerned SPR personnel.

In summary, the Bryan Mound ESR/SPR withdrawal capabilities with the noted exceptions, appear to meet design specifications.

weeks Island Mine - A limited assessment of the Weeks Island system indicates that the proposed system is sized properly for withdrawal rates up to 590 MBPD. However, potential oroblem areas are:

- 1) Since the crude oil must be pumped from the lowest point, if stratification and/or precipitation occur in the crude oil which causes a bottom layer to form with different fluid properties, system performance degradation is possible,
- 2) At the highest permissible flow rates, pressures in the 36 in. pipeline to the St, James terminal are near the design limits. Adding two additional pumps as proposed in future expansion plans could cause the pressure to exceed pipe specifications,
- 3) A number of potential failure modes were identified, e.g., during fill, in the event of an onsite pipe break coupled with a power failure, there is no single onsite valve to shut off flow. The manual valve is five miles away.

Recommendations on the site withdrawal capabilities are:

- 1) In terms of site withdrawal system design, the compatibility of the site/group capabilities with the external distribution system are of critical importance. This emphasizes the importance of the ongoing distribution systems analysis.
- 2) In general, there are numerous site operating configurations that can be used to withdraw oil at a given rate. In addition, it is anticipated that rates other than the design maximum will be required. To assist in operating the system safely and economically, it is recommended that a network flow computer model of each site be developed and used by site personnel during withdrawal.

This should be an integral part of the operating system of instrumentation, controls, and procedures.

 Actions underway to conduct failure mode analysis on all sites should be continued.

B) Site Electrical Power

The adequacy and reliability of the commercial electrical utility service and adequacy of the site electrical distribution system determine the availability of all **onsite** normal operational power. To date, electrical designs have been completed for the ESR and expansion phase for all sites. Portions of the designs have been implemented and others scheduled. Qnly the designs and documentation for the three existing cavern sites were reviewed in this study. Construction of the electrical system is underway, and it is our understanding that changes to the electrical system design are occurring, The conclusions reached are based only on the design drawings as they existed January I, 1979.

Conclusions are as follows:

- 1) The commercial power at the sites is sufficient for the site electrical requirements. The general reliability of the power distribution to the sites should be adequate,
- 2) A minimum number of questions were noted concerning the site designs. These were primarily in the areas of lightning protection at utility interfaces and around hazardous areas, and the necessity of several long cable runs and associated voltage drops at Bayou Choctaw. The lightning protection would normally be provided by the utility but should be verified, and the design necessity of the long cable runs should be checked.

C) Pumps and Motors

Adequate and reliable pump and motor subsystems are essential to all phases of SPR storage site operation; i.e., oil injection, oil withdrawal, and new cavern leaching,

Pumps on hand and planned for the sites appear to have adequate capacities. Studies have shown that pumps and motors of the types and sizes used can be very reliable. Normal repairs can be made within a few days. Groups of pumps for all SPR sites include at least one plumbed in spare for each pumping function. With demonstrated pump and motor reliability, one spare unit for each pumping function, and normal repair times, SPR site downtime due to pump or motor failure should be acceptable. Previous problems experienced with pump/motor units should be eliminated in the future by revamped installation, maintenance, and operating practices.

D) Site Instrumentation and Control Subsystem

The site instrumentation and control subsystem provides the interface and communication between the site hardware systems and the site personnel. Deficiencies and/or failure within the instrumentation and control subsystem can negate or delay the ability of personnel to effectively operate the sites.

At the three existing cavern sites, ESR program site instrumentation and controls have been designed. Assembly and installation are under way. Proposals for the expansion phase have been recently submitted.

Conclusions from the assessment are as follows:

- The design, with certain additions and/or changes proposed in the recommendations, can meet the needs of the SPR site requirements, and
- 2) Operation and control of the site via the site instrumentation system requires understanding fluid flow and permissible velocities, resulting pressure drops, flow control, diagnostic messages, etc. The demands on operating personnel will require detailed operating procedures and highly qualified operators.

Recommendations are:

- Determine if a requirement exists for a SPR central command and control and/or monitoring system. If needed, the design, hardware, and installation should proceed as soon as technically feasible,
- 2) Proceed with the generation of the necessary site operating manuals, from which a better determination of the operator demands can be made,
- Add pressure transducers and alarms on oil and brine control valves where required, and
- Add sonic flow instrumentation to the output of all large pump units to assist in diagnosing reduced performance.
- E) Long-Term Monitoring of State-of-Health

There are three phases in the SPR oil storage cycle: 1) fill, 2) standby, and 3) withdrawal. The loss of, or inability to move the oil during any phase is potentially catastrophic to the SPR goals. Long-term monitoring of state-of-health is concerned with the quantity and quality of the stored crude oil and the condition of the storage cavern/mine during the standby phase.

Efforts completed or planned relative to long-term quantity and quality concerns are:

- 1) Future plans call **for** metering and sampling crude oil upon site arrival or withdrawal. Quantities of crude oil placed in each cavern are presently recorded,
- 2) Cavern **volumes** have been estimated from sonar survey data, and
- 3) Two sets of surface subsidence measurements have been made at Bayou Choctaw. These **may** aid in predicting any remote possibility of cavern failures.

These efforts are just the beginning of what is considered necessary. While emphasis has rightfully been directed to the ESR fill phase, planning and necessary programs for long-term monitoring of state-of-health have **not** received the **same** priority.

Technical concerns or **problems** relative to the standby phase which **have been** identified are as follows:

- 1) The quantity of crude oil actually available for withdrawal is only roughly estimated from (1) and (2) above. Although a remote possibility, leakage from any cavern cannot be easily detected,
- 2) Periodic samples of the crude oil from different depths cannot **be** obtained and analyzed to ensure the oil quality or detect any detrimental changes,
- 3) In the event of serious OK impending catastrophic problems with a cavern or the oil in a cavern at any site, there is no alternate storage or other means to allow immediate withdrawal of the oil in question, and
- 4) While the possibility for cavern collapse is remote, surface subsidence measurements which could provide warning have been initiated at only one site.

The major recommendation from this assessment of the ESR/SPR sites is to Plan and implement a long-term monitoring, of state-of-health capability. This should include as a minimum:

- 1) Extend the surface subsidence measurements to all cavern areas and sites,
- Detail the schedule and provide the hardware for obtaining crude-oil samples at various depths from all caverns, and
- 3) Analyze the cost effectiveness of excess cavern storage sufficient to allow transfer of the stored oil from a threatened cavern. This would also permit an accurate

measure of the oil available for withdrawal. Also, this storage volume can store brine to be used to displace oil from selected caverns which would have limited life if raw water was used. Finally, excess storage would result in a means of sampling all oil within a cavern during an oil transfer.

Special purpose monitoring may be required to provide data to address specific concerns. Examples of these are noted in the long-term cavern stability and the geological/site characterization discussions.

V. SYSTEMS ENGINEERING' MANAGEMENT

W thout being an active participant in the SPR Program, it is difficult to develop a quantitative evaluation of management capabilities and problems. The following observations of management practices are presented and are accompanied by some recommendations.

A) Assistant Secretary for Policy and Evaluation/Office of Emergency Response Planning

It does not appear that program requirements have been formulated at a rate necessary for the scheduled program implementation. We are not certain as to the division of responsibility, if any, for the formulation of all requirements between the DOE Office of Emergency Response Planning and the SPR Program Office. We recommend that this area be reviewed and that those requirements still in a state of development be established to assist in the orderly implementation of the SPR Program.

B) SPR Program Office

The SPR Program Office has overall responsibility for the SPR Program and for assuring that the system is developed in accordance with the requirements. Program implementation has been affected by lack of and/or changing program requirements, a situation compounded by the fluctuating circumstances of world crude-oil supply. This has stressed the capability of the Program Office to continuously reevaluate and update system criteria.

Recommendation - Additional capability should be acquired by the Program Office to continually develop and evaluate system criteria.

C) Project Management Office

The SPR Project Management Office is responsible for site acquisition, design, construction, oil acquisition and transportation, site fill, and operation and maintenance of sites and facilities.

There appears to be a need for stronger systems engineering management to analyze, integrate, and coordinate these responsibilities. Present staff effort appears to be primarily expended in managing day-to-day problems associated with meeting fill schedules.

The following major recommendations are made:

- 1) Establish a strong **systems** engineering/systems integration organization. Major activities would include:
 - Review and develop where necessary overall ESR/SPR system performance criteria,
 - b) Define major system interfaces based on existing designs,
 - c) Review existing drawings and specifications for completeness, accuracy with respect to installed hardware, functional performance, and interface compatibility,
 - d) Evaluate through independent analysis the site, group and system designs against performance criteria,
 - e) Define requirements for new designs with options and cost and schedule impacts,
 - f) Establish a complete and organized library of all SPR documents, drawings, and specifications,
 - g) Establish a formal drawing change and dissemination procedure and review new designs prior to SPR approval,
 - h) Provide a technical overview of construction,
 - i) Review plans for turning a **system** over to the operating and maintenance contractor, and
 - j) Review formal system operating/control procedures against performance criteria.
- 2) Develop an implementation schedule with realistic time estimates. These estimates must be made by the organization and individuals assigned responsibility for each activity defined in the program plan.
- 3) Establish a technology support group separate from the day-to-day activities to address the long-term technical concerns and provide a sound base on which the project continues. This group would support the systems engineering and integration. Activities would include:
 - a) Geological/site characterization,

- b) Geomechanical stability investigations,
- c) Process development; e.g., the three-well leach/fill,
 and
- d) Crude-oil stability investigations.

VI. SUMMARY OF MAJOR RECOMMENDATIONS

- 1. The reserve size and **drawdown** rate **must be** established by the Office of Emergency Response Planning.
- 2. The systems engineering management of SPR should be strengthened either by increasing the capabilities of the SPRPMO (Project Management Office, New Orleans) or by delegation to a systems engineering contractor.
- 3. Additional capability should be acquired by the SPRPO (Program Office, Washington) to continually develop and evaluate program requirements; completion is needed of the analysis of the SPR system with the national petroleum distribution system.
- 4. Selection criteria for the turnkey storage sites should include considerations of the SPR distribution analysis; selection criteria and/or site implementation should include adequate geological site characterization and geomechanics assessments.
- 5. Geotechnical capabilities of the SPR organization should **be** significantly strengthened.
- 6. A geological site characterization plan for existing sites should be developed and implemented.
- 7. The single-well leach/fill method for expansion cavern creation should be reconsidered. An alternate lower-risk plan to the three-well method should be developed under any circumstance.
- 8. Highest priority geomechanical recommendations include:

West Hackberry cavern #6 should be recertified before future use (SPR efforts are underway). The effects of depressurization (during the fire) on this cavern should be assessed. Depressurization effects in certain other caverns should be understood before intentionally allowing this condition to exist.

The impact of Eryan Mound cavern #3 on adjacent caverns should be addressed (SPR program definition efforts are underway).

An operational agreement with Allied Chemical governing Bayou Choctaw cavern #17 should be obtained to assure cavern #15 integrity.

At Sulphur Mines determination of edge-of-dome relative to caverns X6 and #7 should be completed prior to any fill-withdrawal cycle.

A more thorough assessment of the impacts of the planned spacing of the SPR expansion caverns is warranted in order that operations can be planned accordingly.

A plan should be developed and implemented to obtain site specific salt properties to be used in the design of new caverns and the evaluation of existing caverns.

- 9. The current crude-oil stability program should be continued and expanded to include: sampling and recording crude oil being stored in each cavern/mine and periodic sampling and analysis of the crude oil in storage, to determine if the physical/chemical state is changing or if biodegradation is occurring.
- 10. A capability to monitor the long-term state-of-health of the crude oil and the storage caverns/mines should be developed.
- 11. Onsite excess storage for crude oil should be considered for possible emergencies.
- 12. Flow network models for each site should be developed (has been initiated).
- 13. The effort initiated during this study to develop an overall Program Plan (PERT) should be carried to completion.
- 14. The design drawing and document control systems should be upgraded.

Appendix A

List of Principal Investigators (and Contributors)

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Recommendations on Systems Engineering Management

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Appendix B

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Appendix C

PROGRAM ASSUMPTIONS AND CRITERIA

This appendix discusses one issue in more detail. The selection of solution mined salt caverns as the storage media and consequently, the concentration of SPR on the Gulf Coast, is examined.

Type of Storage and Geographical Location

The type of storage and geographical location of the first several hundred million barrels of oil have been determined by SPR personnel and storage is proceeding as rapidly as the engineering aspects will allow. There remains some ability to change the choice of storage media for the remainder of the reserve if it can be proven that another method of storage is more desirable. At this time, it is unlikely other storage media will prove to be superior to solution mined salt dome storage.

Three areas of concern can change this conclusion. First, the choice of salt dome storage is closely linked to the choice to concentrate the SPR system in the Gulf Coast region and it is possible that the distribution system requirements may dictate that some fraction of the reserve be placed elsewhere. Second, technical problems associated with long-term storage of oil in salt domes could either preclude the use of salt dome storage or, more likely, lead to the third concern which is increased cost of salt cavern storage. If the cost of solution mined salt dome storage continues to increase as it has since 1975, other storage media may become competitive.

These increases in costs are the the primary motivation for performing this review. Initial estimates of solution mined salt dome storage costs ranged from \$.70/bbl to \$2.00/bbl [C-4,C-5]; current estimates are approximately \$4.00/BBL [C-6].

The initial criteria for selection of the storage media were the time required for development, cost, safety, environmental acceptability, and distributional acceptability. The oil storage options will be reviewed with respect to each of these criteria.

A desire to immediately implement the SPR has been a major driving function since the project began. The US recognizes its vulnerability and wants to minimize the probability of an oil supply interruption that can lead to severe economic impacts. Additionally, the real cost of oil continues to increase and delays mean higher purchase costs for oil. Existing solution mined caverns in salt domes were and still are the largest immediately available storage facilities. The purchase of the sites allows for expansion by solution mining new caverns. While delays have been experienced

in the acquisition of the salt domes, there is no reason to expect the acquisition of other types of storage media to **be any** less involved.

Existing rock mines are not available in the quantities and locations that are desirable, and certification of the mines for oil security is difficult [C-5]. New rock mines require three to five years of construction [C-4,C-7]. Sufficient quantities of excess above-ground tank capacity are not available and it is estimated that the steel tank industry would have to be dedicated to the SPR program for more than eight years to produce 500 MMB of storage [C-5]. Salt caverns appear to have been and continue to be the most immediately available storage media.

In every study performed, salt dome storage has consistently been the most economical method for storing large quantities of oil [C-4,C-5, C-7,C-81. Even given the current cost estimate of \$4.00/bbl, it is more economical than other storage methods which are estimated to cost at least \$6.00/bbl. As corroborating evidence, a LOOP study in 1976 estimated new solution mined salt caverns to cost \$3.86/bbl. This included a brine storage reservoir and a much larger site distribution system [C-8]. While this indicates that initial SPR and National Petroleum Council estimates were too low, current estimates are now consistent with LOOP's projected costs.

The **major** environmental impact for salt caverns is brine disposal. The disposal of equivalent **volumes** of rock generated by rock excavation cannot **be** any easier. Tanks require **huge** quantities of land and are generally considered to be an eyesore. They also present a higher potential for air and water quality degradation than underground storage methods [C-8].

Salt domes occur in the region of the country that is probably the **most** advantageous for crude-oil distribution. Salt domes have been purchased that are near both **major** interstate pipelines and ports.

Underground storage is preferable to above ground storage for both safety and security. The West Hackberry fire is an ironic example of the inherent safety and security of underground storage. Approximately 33,000 bbls of oil were lost while the fire raged on top of a cavern filled with 7 MMB of oil. If the same fire had occurred in a tank farm, much larger quantities of oil would have probably been lost. Underground storage should also be less vulnerable to natural disasters, such as hurricanes and floods.

In conclusion, **solution** mined salt dome storage of oil appears to be equal or superior to any alternative for every individual criterion.

Appendix D

Geological/Site Characterization

The geological/site characterization study is concerned with geologic evaluation pertaining to the initial selection of domes, site characterization, cavern stability, and brine disposal. The investigation of these areas relied on reports, office interviews with SPR Personnel, contractor representatives, and site examinations at Weeks Island and Bryan Mound. An annotated list of reports reviewed was compiled and is included as Appendix Q. Interviews with the geological staffs of the several companies who hac either mined sulfur from the caprock or had solution mined cavities at the three ESR sites could not be held due to the possible affects on current land condemnation proceedings involving the companies and the government. Unfortunately, this may have resulted in the denial of important and possibly unique information relating to geologic evaluation efforts. There are only four reports [D-1 - D-41 available that deal with the overall geologic settings of the existing sites. It is implied in the feasibility reports [D-2,D-3] that detailed geologic evaluations would continue once a particular dome was selected for the SPR program. This appears to have been done only for the Bayou Choctaw site [D-4]. In the case of the Bryan Mound report, there was some basis for assuming that either Freeport or Dow Chemical, currently utilizing the site would be involved in the detailed evaluation.

The fact that no central geological department exists within SPR hindered the data collection effort. Some maps pertaining to the geometry of individual caverns were available but these did not pertain to the overall dome geology. Additional studies *and* geological information were available through Gulf Interstate, Lou is Records, and PB/KBB reports and contacts. As a representative case Bryan Mound was selected for a detailed assessment of the requirement for, and the status of, geological site characterization.

Proposed Comprehensive Site Characterization Program

A comprehensive site characterization program should consist of six study areas with each area divided into two phases. The first phase in each area consists of the compilation and analysis of existing data. This effort would rely on data sources available in either public or private records with particular attention paid to the data held by companies active on the site. The data analysis efforts would result in identifying portions of the site requiring further study. The second phase of each study area would be primarily concerned with the completion of the studies identified in phase one. A description of the study areas in the comprehensive site evaluation program follows.

- 1) Surface Geological, Geographical, and Hydrological Study The objective of the study is to characterize the land and near surface geology and hydrology. This would include topography, premining reviews, effects of sulfur mining, soil distributions, and hydrological characterization.
- 2) Caprock Geological, Hydrological, and Geophysical Study The objective is to quantify the effects of sulfur mining and mud-filling and to assist in predicting drilling problems, future subsidence, or possible cavern collapse or casing leakage. Activities would include sulfur mining characterization, groundwater analyses, and reviews of previous caprock connected operations.
- 3) <u>Salt Dome Geometry Study</u> The objective is to accurately map the dome boundaries and interior through the zone of interest. This would entail sophisticated seismic profiling, and structure and sediment mapping.
- 4) Interior of Dome Study The objective is to understand the interior makeup of the salt dome by analysis of drill records. (old and new), salt cores, and general caprock formation data. Another activity would be the review and current assessment of the cavern certification process.
- 5) Geological Studies Related to Brine Disposal The objective is to select and characterize the available aquifers for brine disposal purposes. It would be necessary to review data, compile subsurface information, and possibly initiate new test drilling programs.
- 6) Coastal and Marine Study The purpose of the study would be to address possible effects on the geology due to natural events such as hurricanes, and to assess actual damages where feasible. The ultimate effects on pipelines, etc. would be estimated. Emergency plans with regard to site operations would be initiated.

Considerable site specific work may be necessary to complete an overall geological assessment. A series of surface and possibly subsurface monitors may be necessary to determine effects of leaching, filling, and recovery operations. Special studies are appropriate for particular problems such as posed by existing caverns (examples include caverns #3 and #5 at Bryan Mound) or brine wells. The overall compilation of information should be used in a geologic hazard and emergency plan review. This would be an important input to the safety evaluation and emergency preparedness task force results which have been completed by the DOE.

Comparison of Proposed Comprehensive Site Characterization Program and Current Status of Bryan Mound

A comparison between the proposed comprehensive plan and the current status of Bryan Mound is presented in the Table D-l. The reader

must realize that the comparison is subjective in nature. A review of the comparison will reveal that most of the major components required for a comprehensive site characterization at Bryan Mound have not been accomplished to date.

It should be noted that geotechnical concerns have already arisen at Bryan Mound because of geological unknowns. The two major concerns are the unstable fluid conditions in cavern #3 and the anomalous zone of highly insoluble material in cavern #5. Uncertainties in cavern and dome dimensions, noted in the next section, also have an impact on understanding long-term cavern stability.

Assessments

Based on the review of geotechnical reports and the detailed assessment of Bryan Mound, the following conclusions have been drawn:

- 1) No comprehensive geological studies have been completed for the Bryan Mound site. Similar conditions appear to exist at the West Hackberry and Sulphur Mine sites. The most extensive geological descriptions of these sites were contained in the original feasibility reports which implied that additional geological investigations would continue.
- 2) The geological studies for the Bayou Choctaw site [D-4] are more comprehensive. However, these studies revealed that cavern #20 was close to the edge of the dome and more detailed investigations were warranted,
- Except for the Bayou Choctaw site, subsequent geological investigations have been problem specific, and

Recommendations

- 1) Establish a geoscience capability to conduct and/or direct long term geological, geophysical, and hydrology studies and to assist in solution of geotechnical problems.
- 2) Perform a geological site characterization comparison (similar to that done for Bryan Mound) for the other sites.
- 3) Develop a sufficiently comprehensive geological/site characterization plan and implement it for all sites. While it would have been desirable to have completed geological studies prior to oil fill in existing caverns and initiation of the expansion program, the studies are still necessary.
- 4) It is our understanding that a geological and geotechnical evaluation is required with each turnkey proposal. However, because of the high cost, an in-depth evaluation cannot be provided at the proposal stage. Contracts for selected sites

STUDY SUBCLASS STATUS COMMENTS

Surface Geological, Geographical, and Hydrological Study

Current Topography	Partial	Detail Maps Only Near Construction Sites
Establish Survey Baseline	Complete	
Pre-Sulfur Mining Topography	Not Planned	
Land Subsidence and Fill Map	Not Planned	
Man-Made Structures	Complete	
Land Ownership	Complete	
Surface Water Quality	Not Planned	
Surface Water Flow	Partial	
Soils Map	Partial	Soils Mapped Only at Construction Sites
Test Drilling	Partial	Soils Tested Only at Construction Sites
Storm and Flood Damage	Partial	Studies Only for "Normal" Weather Cycles

Caprock Geological, Hydrological, and Geophysical Study

Premining Maps Top of Caprock Top of Sulfur Bottom of Sulfur Top of Salt	Not Planned Not Planned Not Planned Not Planned Not Planned	
Pos tmining Maps	Not Planned	Only Maps Available are from a 1926 Summary
Same Set as Premining	Not Planned	Geologic Report
Isopacs	Not Planned	
Mud Fill Map	Not Planned	
Cross Sections	Not Planned	
Survey Plat of Holes	Not Planned	
Well Records	Not Planned	
Geophysical Survey	Not Planned	

TABLE D-1 (cont'd)

STUDY SUBCLASS	STATUS	<u>COMMENTS</u>
Salt Dome Geometry Study Conduct High Resolution Seismic Studies Plan Maps Cross Sections Salt Contours	Not Planned Not Planned Not Planned Not Planned	Only Maps Available are from a 1926 Summary Geologic Report
Interior of Dome Study		
Well Records of Holes Into	Partial	Records Not Fully Interpreted
History of Brine Wells Plan and Participate in Cavern Certification	Requested Partial	DOE Seeking Information from Dow
Geologic Conditions Near Caverns	Not Planned	
Geological Input to Cavern Spacing	Partial	
Sample Collection Sample Testing	Complete Not Started	Cuttings and Core Samples are Being Stored and Not Analyzed

TABLE D-1 (cont'd)

STUDY SUBCLASS STATUS COMMENTS

Geological Studies Related to Brine Disposal

Prepare Geologic Cross Sec-	Partial	Some Subsurface Studies a	t Selected Locatio
tions and Recommendations	3		
for Stratigraphic Position as	na		
Location for Brine Disposal			
Conduct "Medium" Size Hole	Not Planned		
Drilling and Testing of			
Potential Disposal Zones			
Report Findings of Test Pro-	Not Planned		
gram			
Recommend Well Completion,	Partial	Well Design is Excellent,	but Required
Number of Wells, and Best		Capacity Exceeds Well C	apability.
Locations for Brine Dispo-		Pretreatment of Brine i	
sal Well Fields			-

Coastal and Marine Study

Shoreline Modification due to Natural Recession and Hurricanes	Not Planned	The Only Mention of These Type Studies is in
Geological Inputs in Selection of Pipeline Rout-	Unknown	the EIS.
ings On and Off Shore Geological Input to Site Emergency Plans	Unknown	

- snould include adequate provisions for geological assessments which should be completed before initiation of major construction and oil storage.
- 5) A central file of geological reports should be developed within the program and personnel responsible for the sites should increase their familiarity with what geological data exist within SPR.

APPENDIX E

Long-Term Cavern Stability Evaluation

The long-term stability of SPR (Strategic Petroleum Reserve) caverns is essential to assure that serious failures will not occur. Such a failure could cause severe environmental impacts, economic losses (crude oil or facilities), or could prevent withdrawal during a supply interruption. The ESR utilizes existing caverns with shapes and spacing significantly different from those designed for hydrocarbon storage. This observation should not imply that these caverns are unsuitable for crude-oil storage but rather that there be a thorough understanding and evaluation of these caverns in order to assess any potential for occurrence of failure.

This evaluation of the geomechanical stability aspects of the ESR/SPR caverns is based upon detailed discussions with SPR project personnel and contractors, evaluation of the SPR-sponsored work reported to date, comparison of the SPR program with other industrial and governmental storage programs, supporting measurements made in the laboratory, and numerical simulations. In summary, it was observed that **signif icant** effort has been expended by SPR contractors in addressing the geomechanical aspects of the design, certification, and evaluation of solution mined caverns. These test programs and geomechanical investigations were found to be thorough and adequate in many areas. However, the SPR documents as well as this study have defined areas in which additional investigations are recommended. The basic conclusion offered in this evaluation is that final design of the new caverns and evaluation of the existing storage caverns should parallel an expanded and well coordinated geomechanical investigation that addresses site specific questions. The remainder of this appendix is devoted to describing the evaluation which led to this recommendation and to other programmatic and site specific recommendations.

Summary of SPR-Sponsored Investigations

A myriad of documents have been prepared by SPR contractors and SPR personnel on the geomechanical aspects of the design, certification and evaluation of solution mined caverns. The techniques used in the geomechanical studies are briefly described, the laboratory results obtained to date are discussed, and the recommendations for further work are noted. The feasibility studies [E-1] and the environmental impact statements [E-2-E-4] for the SPR program contain general statements regarding a geomechanical approach to the construction of new cavities and contain only sketchy information regarding investigations of existing cavities. The cavern certification reports [E-5-E-19] contain valuable information detailing the results of sonar surveys for

determining cavity shapes and describe in detail the pressure tests performed on each cavern. The most complete treatment of cavern stability aspects of the ESR caverns at the four sites is contained in Ref. E-20. In addition, during 1978 site specific reports [E-21, E-221 were issued by PB/KBB, a DOE contractor, which delineate the studies performed by them and the laboratory testing conducted to date. For general reference, a brief description of the new caverns and the existing storage chambers is contained in the testimony presented [E-23] before the Louisiana Department of Conservation while a more detailed summary of the design of the new caverns is in Ref. E-24.

The site certification documents [E-5-E-19] serve as the most complete source of cavern geometry information and accurately document the testing and surveying programs adopted for each cavern. Considerable efforts were expended to pressure test the caverns and well casings, run cement bond logs, perform sonar caliper surveys, and gyrostabilized azimuth and deviation surveys on the certified caverns. The certification reports were found to be very thorough and complete. In many instances however these documents mentioned additional work which should be performed before oil was either stored or in some cases removed by fresh water cycling. The recent studies [E-21,E-22] by PB/KBB address some of the questions raised in the certification documents. certification documents continually refer to the fact that "an certification documents continually refer to the fact that "an attempt is to be made by another contractor to take an actual measurement at a reduced loading (pressure) on the roof which could be encountered during operation of the cavern". Since no subsequent reports detailing results of these tests were obtained by Sandia, we conclude that these tests have not been performed. Cavern \$15 at Bayou Choctaw was not certified by DOE prior to oil storage. The certification tests were performed on brine filled caverns and represent an excellent starting point from which to pursue further evaluation of existing caverns as regards their suitability for crude-oil storage. These tests must not be interpreted as being an endoresment of either the ability of a cavern or casing seat to Since no subsequent endoresment of either the ability of a cavern or casing seat to withstand the unique loading conditions associated with depressurization during crude-oil storage or the stability or pressure tightness of a cavern when it enlarges as a result of the use of fresh water to displace the oil.

The cavity closure assessment reported in Ref. E-20 delineates factors which affect the stability of storage caverns, describes four instances of Gulf Coast domes in which gross structural failures of material overlying salt cavern8 resulted in collapse feature8 at the surface, and cites ways in which oil might move upward from the cavities. The instances in which surface depressions resulted from cavern collapse were all for facilities (3 cavern8 and 1 mine shaft) which were less than 300 ft. deep. A cavern by cavern assessment is made of the adequacy of the roof material. In additon, the size of the brittle and plastic zones which exist in the region8 surrounding an isolated cavern is calculated. The evaluation of the ESR cavern8 is based upon analytical expressions presented in [E-25-E-27] that were developed primarily for

cylindrical caverns with hemispherical or arched shaped roofs. The authors give no attention to differences which might result from the flatter roofs which some caverns in the ESR program (West Hackberry #6 for example) have. In addition, cavern to cavern interference effects are assessed by superposition of results from isolated cavern analyses. The authors mention that their equations are not valid for conditions in which two adjacent caverns experience different pressures and although they postulate that the effect of a pressure differential would be second order compared with the effects of either cavern's hydrostatic pressure they state that "in cases where the wall is already near its buckling point, however, the application of such an unbalanced force could possibly initiate wall failure and thus should be avoided". A more detailed evaluation of these effects is provided in a subsequent section of this appendix. Significant differences are noted in cavern geometries (diameters and heights) and spacings used in this study when compared with the cavern certification documents. There appears to be no pattern to the differences (i.e., differences do not always favor either enhanced or diminished stability) so careful correlation of these results with the actual cavern shape and spacing parameters appears warranted. Little consideration is given to assessing the effects of cavern coalescence except to note (Figure E-l) that the blanket of oil in the lower cavern might be lost. The authors cite the need for an early warning system for assessing impending cavity collapse and state that "it would appear prudent to install a monitoring system at each cavern to detect slabbing". This recommendation for expensive monitoring of each cavern almost appears to conflict with the major conclusion of the study that the likelihood of a collapse of an oil storage cavern in salt appears to be remote.

In a study of the salt dome geology and stability of the caverns at the Bayou Choctaw site [E-21], field, laboratory, and numerical investigations are reported. Recommendations are made regarding the utilization of existing caverns at this site and regarding additional efforts which should be expanded to ensure satisfactory storage. For example, recommendations are made regarding cavern #15 to obtain surveys of #15 and #17, a nearby cavern owned by Allied Chemical Company in which ethane is stored, and to either acquire cavern #17 or to obtain a working agreement with Allied regarding usage of this cavern. Significant risks of collapse are noted for caverns #2 and #4 (not in SPR storage plans) so it is recommended that no surface facilities be located above the zone of influence of these caverns (implemented by SPR).

The laboratory testing done for PB/KBB appears to have been conducted on cores from the Bayou Choctaw site [E-21]. Bulk density, moisture content, ultrasonic velocity, uniaxial and triaxial compression, and indirect tension data were obtained. Failure strains of up to 20% were noted in the salt but less than 1% was typical of caprock specimens. Young's modulus for the salt averaged 3.35 Mpsi while Poisson's ratio was .26. The cap-

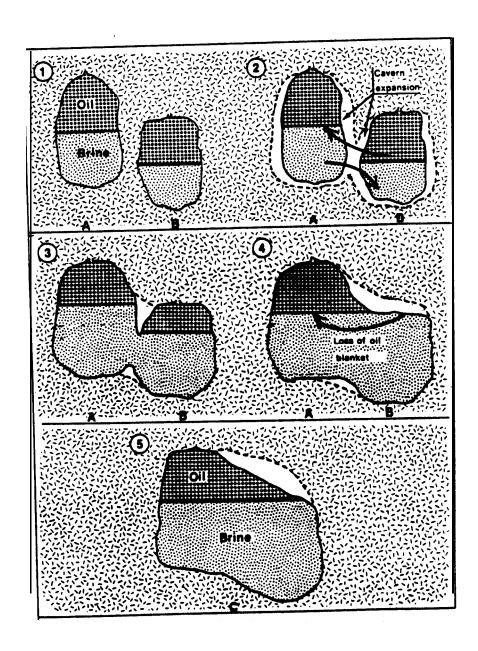


FIGURE E-1. Mechanisms for Loss of Oil Elanket During Coalescence [E-20]

rock values were 2.28 Mpsi and 0.29, respectively. No creep tests were performed. Additional testing may have been done in Germany since Professor Dreyer, a consultant to PB/KBB, has obtained some samples of the core from SPR sites.

Finite element calculations performed by SPR contractors to assess the stability of the existing cavities have relied solely upon the use of elastic theory. For the Bayou Choctaw site [E-21], a three-dimensional analysis was performed to assess the stress conditions which might exist within the dome. In addition, a two-dimensional simulation of cavern #4 was performed. This cavern is not in the SPR program. This study indicated that there is "a definite possibility of catastrophic collapse at this site." A two-dimensional model of caverns #6 and #7 at Sulphur Mines [E-22] indicates that the roof remains in compression for anticipated ESR loading conditions. This was interpreted as implying that roof spalling would be unlikely under normal operating conditions. No site specific material property data was used in these calculations and no creep deformations were simulated. The stress fields calculated in these studies should, however, be fairly accurate since the analyses made by Sandia on cavern #6 at West Hackberry (described in a succeeding section) indicate that only small changes occur in the stress components near a cavern as a result of creep. The deformation behavior of the caverns, however, is (based upon the West Hackberry cavern #6 calculations) dominated by the creep motion. No assessment was made of the stability of the caverns using the "worst case" scenario that no oil or brine head would exist at the casing seat (i.e., if there were a failure of the casing or the grout at this depth).

Stability criteria are put forth in the Sulphur Mines site report [E-22] which are used for the evaluation of the existing cavities. For the roof area, the salt thickness to the caprock divided by the span of a cavern is preferred to be at least 1. However, 0.5 reportedly may be considered acceptable when site specific details are considered. No mention of the "site specific details" is presented and no procedures for site evaluation are described although it is presumed that reference to roof shape and salt properties is made. This criteria is deemed applicable only for spans up to 500'. Beyond this span, it is postulated that excessive roof deflections may occur which can result in roof spalling. Again, no quantifiable justification for this limitation is provided and no case histories are cited to confirm this statement. A minimum distance between caverns of 100' was deemed acceptable: similarly a 100' distance between a cavity and the edge of the dome was considered to be an absolute minimum. Additional work regarding definition of the dome boundary near caverns #6 and #7 at the Sulphur Mines site is also contained in [E-22]. This evaluation (based upon existing drilling records), however, does not clearly define the location of the dome boundary since it is not in complete agreement with previously published data.

In a recent presentation [E-24] to the Solution Mining Research Institute, Sevenker (representing PB/KBB) described the engineering design prepared by PB/KBB for the Department of Energy. The background and

storage goals of the SPR program were described including the expansion phase. The expansion phase described for the various sites was in regard to current designs and did not necessarily represent fully the DOE construction plans. The new SPF caverns are designed to be initially leached to a 2000' high "flower pot" shape with a top diameter of 230' and an initial bottom diameter of 170'. The six stages of cavern development are shown in Figure E-2. Three wells (75' centers) will be used simultaneously for leaching a cavern. Direct leaching will be used to create the sump and chimney areas while indirect leaching will be used for the roof construction and for the major development of the cavern. Oil will be injected during the leaching process to allow cavern utilization prior to completion of the construction. Periodic sonar surveys will be taken. To provide for cavern creep and to provide a margin, or cushion, an additional 1 MMB of cavern space will be leached (i.e., to ensure 10 MMB of storage space, an 11 MME? cavern is leached). After 5 cycles, the caverns are planned to be uniform cylinders with a 270' diameter and a volume of 20 MMB.

The PB/KBB design for new cavities relies heavily upon the information garnered from testing physical models [E-25,E-26]. In the model tests, the radial convergence of the inner boundaries of hollow cylinder specimens of salt was monitored. The tests were loaded axially by a ram and radially by a thick steel jacket heated to provide the desired radial load. The volumetric convergence, K, formula developed from these tests for tall cavities is

$$K = a(1 - \frac{D}{2H}) (\Delta \sigma)^{d} T^{e} t^{f}$$
 (E-1)

where D is the cavern diameter, H is the cavern height, $\Delta \sigma$ is the difference between the pressure of the oil and the average pressure of the surrounding rock salt, T is **the absolute** temperature, and t is time. The parameters a, d, e and f are material constants. For the salt tested (not SPR salt), Dreyer reported [E-25] the following values for **the** material constants for **K** in **%** closure, Au in psi, T in °R, and t in months

$$a = 9.314 \times 10^{-9}$$

 $d = 1.2$
 $e = 1.7$
 $f = 0.7$ (E-2)

Additional model tests were performed by Dreyer to assess the effects of geometric parameters on the spacing of caverns and upon the minimum allowable roof thicknesses. Unacceptable behavior was defined as the load at which optical clouding was observed in the salt in the roof or pillar regions. The results of these tests were compared to existing cavity design information and examples of use of the data for design calculations was provided. The design of the Neuenhuntorf compressed air energy storage (CAES) facility in West Germany relied upon the use of these bench scale models. Similarly, the design of the

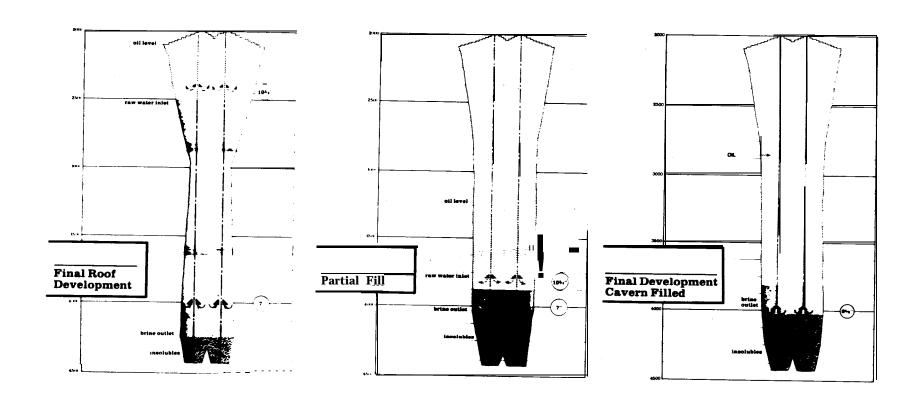


FIGURE E-2 (cont'd). Cavern Leaching Process (From PB/KBB)

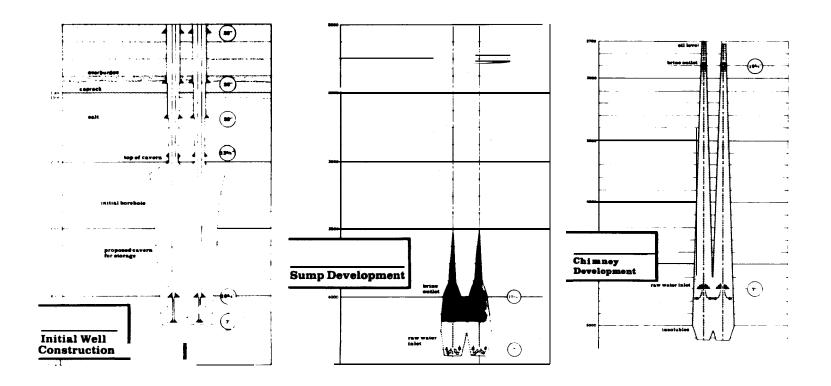


FIGURE E-2. Cavern Leaching Process (From PB/KBB)

German crude oil storage facility at Etzel was based in large part on the physical models as well as on the previous experience of the company's designers. No reports describing physical models of SPR salt were obtained by Sandia; the previous experience of Dreyer in utilizing the model test results in the design of solution cavities was used in the SPR design via his consulting contract with PB/KBB. However, no published reports describing how this expertise was used in setting the new cavern spacing or in evaluating the old caverns have been found in SPR files presumably because the consulting contract was not paid for using SPR funds.

Creep analyses were performed for PB/KBB to simulate new SPR caverns for 30 years following construction. A time hardening version of a primary creep law was used in this simulation. The creep parameters were not based upon tests on SPR salt cores but were obtained from creep tests [E-28, E-291 on samples from the Tatum salt dome in Mississippi. With a brine head, the maximum radial displacement of the cavern wall is computed to be on the order of 10 inches in 40 years. Ambient temperature material properties were used in this simulation. For the 30 year life of a storage facility in order to be considered conservative, (i.e., to bound anticipated deformation rates), the simulations should probably utilize either a steady creep law or a combined primary/steady representation of the salt response and should use material properties applicable for the temperature of the cavern walls rather than assuming ambient conditions.

A field test program for investigating the apparent self-leaching cavern #3 at Bryan Mound has been proposed [E-30]. This study proposes to monitor the fluid level in the cavern well, sample and test the brine at various levels in the cavern and points in time, develop and install a subsidence monitorning system and evaluate the potential usability of high resolution, "state-of-the-art" monitoring equipment. Similarly, an extensive subsidence monitoring program is proposed *over* the Sulphur Mines dome using off-site bench marks for assessing regional subsidence, bedrock markers, and deep surface monuments. Additional field data should be available from West Hackberry #6 if the proposed fluid flow and wellhead pressure monitoring plan for evaluation of selected depressurization levels is implemented. Wellhead pressure data are routinely monitored at the ESR caverns.

A planned coring program [E-31] for the Bryan Mound site in Brazoria County, Texas, describes the coring which will be done in each of the 12 well holes planned for the expansion program. Three 60' long sections will be cored from each hole at staggered depths ranging from 2000' to 4180'. A total of 2160' of core (4 inch diameter) will be obtained during this program. Cutting samples will be taken at 10' intervals in the overburden and the salt, and every 5' in the caprock. A summary of this coring program is reproduced here as Figure E-3. A similar document for the West Hackberry site has been prepared [E-32]. While these coring programs will certainly provide adequate amounts of salt for studying the leaching behavior of the new caverns and the mechanical properties of the cavern walls, some consideration should be given to sampling the roof material in at least one of the holes drilled for a cavern to ensure the competency of this salt.

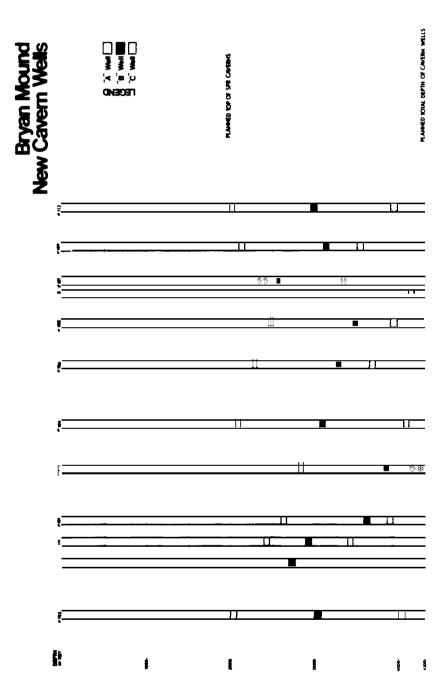


FIGURE E-3. Coring Plan for Cavern Wells at Bryan Mound Dome E-30]

The SPR documents indicate areas in which additional information is deemed necessary. For example, the site certification documents indicate that information should be obtained regarding cavern roof behavior during depressurization and note caverns for which additional efforts are required to better define the edge of the dome. The reports of the numerical analyses often indicate that material property data is lacking, that field validations should be pursued, or that additional analyses could be performed to enhance knowledge of the caverns. Similarly, the information that could be obtained by studying cavern #3 at Bryan Mound is recognized [E-30] as being important to ensuring the integrity of caverns at this site in which oil is stored. Although several investigations which were recommended in earlier SPR documents are underway (i.e., subsidence monitoring, wellhead pressure measurements, etc.), there does not appear to be a comprehensive plan for geomechanical investigations which establishes priorities for individual projects and defines long range objectives for improving design credibility.

Compendium of Related Storage Projects

Salt formations throughout the world are being used (or considered) for the storage of fluids (propane, butane, natural gas, chemicals, crude oil, etc.), gases (compressed air and hydrogen) and solids (such as radioactive waste products). The demand for salt dome storage space is expected [E-33 - E-351 to rise substantially in coming years as these facilities become recognized as valuable elements in meeting future energy needs. The demand for salt caverns for hydrocarbon storage has increased significantly in recent years because of both economic and political factors. A recent worldwide survey [E-36] of current and planned underground storage of crude oil shows rather dramatically the fact that many nations are currently increasing their reserve storage capabilities (see Table E-1). While not all of this expansion of storage capabilities will be in salt; it can safely be assumed that because of economic, environmental, and engineering considerations, domal, anticlinal, and bedded salt deposits will certainly be utilized for the majority of the expansion of facilities.

Valuable information can be obtained by describing other storage projects (completed, ongoing, or planned) and contrasting the design philosophy and limitations inherent in these construction projects with those of the SPR program. This compendium describes other industrial and governmental hydrocarbon storage projects as well as summarizing ongoing programs in the development of compressed air energy storage facilities and radioactive waste repositories. In addition, other related projects and research programs are briefly described. Although these projects are individually contrasted with the SPR program in this section, the subsequent section provides not only a philosophical comparison of the design approaches but also contrasts specific aspects of other crude oil storage projects with the SPR program.

TABLE E-I

Underground Storage of Liquid Hydrocarbons*
(Crude Oil and Some Fuel Oil)

MINI	PRESENT STORAGE (MMB)	PLANNED STORAGE (MMB
Ca <u>nad</u> a	0.4	93.7
Finland	74.4	86.9
Fr ance	62.5	134.5
Great Britain	Unknown	59.7
Japan**	No Underground	No Underground
Norwav/Denmark	13	45
Sweden	7.5	62.9
Switzerland	49.4	49.4
West Germany	62.6	237
TOTAL	269.8	769.1

^{*}Table presented in Ref. E-36, May 1978. Sources used in table development are primarily oil and gas industry magazines and personal contact with various consulates of the countries.

^{**}Japan **now has** 268 MMP stored above ground; **part** is strategic reserve: anticipate 433 MMB by 1980.

Louisiana Offshore Oil Port (LOOP)

The Louisiana Offshore Oil Port (LOOP) project plans to develop 14 solution mined storage caverns in the Clovelly salt dome in southern These caverns will serve as working storage for LOOP, a ort designed for offloading supertankers. The operational deepwater port designed for offloading supertankers. The operational and cost feasibility of this portion of the LOOP project is described in a paper by Bell [E-37]. Some of the environmental aspects of this project and the potential for expanding the facility to provide storage capabilities for national security purposes are briefly described. Initially, there will **be** 8 caverns developed each with 3.5-4 MMB capacity. Ultimately, 14 caverns with a 5 MMB capacity each will be developed. The pumping rates (100,000 BBL/hr) and frequency of use of the proposed facility make the LOOP project The Clovelly dome was selected over other considered sites because of the shallow depth of salt, the symmetrical structure of the dome, and because of the uniformity and density of the caprock. The operating facility will use a brine displacement technique for cycling the oil. Brine disposal from the site will be into the Gulf of Mexico. A cost of \$3.85 per barrel of working storage is estimated for the project. A reference is made [E-37] to a program for test coring in the Clovelly dome to determine if anomalous zones exist within the salt.

Since there was no established design base for optimum spacing and sizing of caverns for stability, LOOP engineers sponsored and carefully monitored a finite element study [E-38] of the 14 cavity concepts to provide some guidance in selecting the size and spacing of the caverns to be leached into the dome. Single, double, multiple cavity analyses were performed to assess potential interfrence effects between caverns. The multiple cavity analysis was axisymmetric with the cavity at the center and the radius of the outer boundary selected to give the same planform area of salt that would exist in a hexagonal packed array of cavities. Parameter variations were made to establish the effects of variations in material properties, cavity depth, and lateral stress. The hypothesized in situ lateral stress was observed to be the most important variable in assessing the stability of the caverns. In evaluating the effects of cavern spacing, three different ratios (P/D - 1, 3, 6) of wall thickness between caverns to the cavern diameter were analyzed. The multi-cavity analysis for P/D = 1 indicated a lack of stability, 1.e., the predicted radial strains of 20-60% would obviously lead to failure. The roof area analyses also indicated that for P/D = 1 the subsidence of the region above the cavity would also be unacceptable. In the conclusions of the report the author warns that his analysis may overpredict the displacements of caverns when P/D is less than 3. He postulates that the load transfer to the rock formation surrounding the dome may tend to stabilize the cavern complex by reducing the salt flow into the cavities, but provides no analysis to support this contention. However, specific recommendations were made regarding design specifications:

- Maximum cavity length should **be** less than 1000' Maximum cavity depth should be less than 2500'
- 2:

- 3. Maximum cavity diameter should be 190'
- 4. Minimum separation distance should be 600'
- 5. P/D ratio is recommended at 2-3

The cavity length, depth, and diameter restrictions appear to be based more upon the size of the LOOP requirements in relation to the platform area of the dome rather than upon geomechanics considerations. The P/D ratio recommendations appear, however, to be the product of this study. The author's major recommendation for further study is that the stabilizing effect of the formations at the flanks of the dome should be investigated.

In the multi-cavity analyses for P/D = 2 (approximately the SPR separation), the LOOP study predicts an upper limit of about 10% radial closure for a slice of a cavity at a depth of 2500°. This is substantially more than the analyses described in Ref. E-21 predicted for the SPR caverns at an even greater depth (about 4000°). The assumption of a high lateral stress in the LOOP study as well as differences in the creep laws could explain the lack of correlation between these investigations. Additional comments regarding these differences are provided in the section on cavern stability evaluation.

French Hydrocarbon Storage Program

A description of the hydrocarbon storage facility developed at the Manosque site in eastern France (40 miles northeast of Marseille) is provided in Ref. E-39. French law compels refiners to store the equivalent of three months consumption. GEOSTOCK was set up as a subsidiary of four French oil groups to design and build the large underground storage facilities required for hydrocarbon storage for use in time of economic need and for seasonal storage of diesel oil in summer for use during winter months. The facility at Manosque is designed for thirty four solution mined cavities in an anticlinal (not domal) salt deposit. The storage project consists of three phases of development. In the first phase, 18 cavities were created by 1973 with a total capacity of 30 MMB. In the second phase, construction of 16 cavities was to double storage capacity by 1976. Stage 3 is reported as depending on future seasonal needs or shortages.

The salt formation at this site exhibited considerable discontinuities. The salt bearing formation in the anticlinal zone varies in thickness (averages about 2600') over approximately a 1.25 x 2.5 mile area. There are no diapiric zones. A competent anhydr i te layer overlies the salt formation. In the first phase, pear-shaped caverns of 1300' height were developed between depth of 2000 and 3300'. Insoluble materials (anhydrite and others) which were formerly part of the overlying materials are not observed to be broken into pieces ranging in size from 4-40 inches (and larger). During the development of the caverns, these pieces of material become detached from the walls and fall to the bottom of the caverns. It was reported that the bottom of the cavities were filled with these insoluble materials and it was implied [E-39] that brine strings were occasionally damaged by the eddies formed by this falling debris. Cavern development wells were kept to within 2° of vertical, Al 1 developed caverns were pressure tested prior to storage. No mention is made in Ref. E-39 of the cavern spacing or the cavern diameter: however,

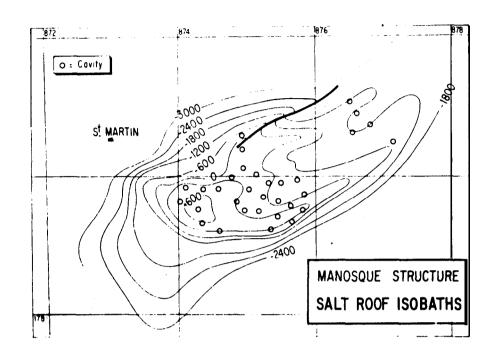
for a 3 MMB cavern that is a 1300' high cylinder, the average diameter would be 130'. The drawing in Figure 4 (taken from Ref. **E-39)** indicates irregular shaped caverns; such shapes would be anticipated in regions where large **amounts** of insolubles are present. This figure (if drawn to scale) indicates a relatively large spacing (P/D greater than 3).

In an analysis to forecast how the cavities behave after filling, the pressure was kept constant on the oil side and monitored for more than a year after filling. Comparisons between the volume of brine withdrawn to maintain constant pressure on the oil side were made with the reduction of the apparent volume of the chamber due to thermal causes. These comparisons showed, for the single cavern described, an equivalence to within 600 BBL, thereby indicatting that there was little, if any, creep deformation occurring (less than .04% volume loss per year). The adequacy or accuracy of the calculations made in this assessment cannot readily be discerned since Ref. E-39 does not provide sufficient details.

The French and US programs for crude-oil storage are similar in certain areas, i.e., salt formations are used, oil blankets are inserted for roof control, there is a three month withdrawal time, and cavern depths are similar. The major differences which appear are the type of salt formation (anticlinal vs. domal); the storage requirements are placed upon the industrial sector in France, whereas US storage is owned and operated by the government and its direct contractors; and the French developed and certified all caverns prior to filling (i.e., no simultaneous leach-fill operations). Differences in the cavern stability considerations in the US and French programs are difficult to discern from the information presented in Ref. E-39. However, one major difference noted is the lack of creep closure observed in the French cavern, i.e., cavern deformations are considered elastic. Further evaluation of the wellhead measurements and the interpretative analyses should be obtained before accepting the idea that creep response is so minimal in the French caverns. Flat cavern roofs are used in the French caverns while more stable, nearly hemispherical roofs are anticipated in the SPR caverns; the small span of the French caverns keep this difference from being an influential design parameter. The walls of the French caverns are more irregular than anticipated in the SPR caverns due to the presence of more impurities; correspondingly, the sump areas for the French caverns are much larger than the SPR design drawings indicate.

West German Crude Oil Storage in Etzel Salt Dome

The development of West Germany's underground crude oil storage project at the Etzel salt dome southwest of Wilhelmshaven in northwestern Germany is described in Ref. E-40 (see Fig. E-5). Thirty three caverns were developed below a surface area of 568 acres at a rate of about 100,000 BBLS/day. Each cavern has a 3 MMB storage capacity. This storage project was initiated in late 1971. After about 2-1/2 years of construction, solution mining of the



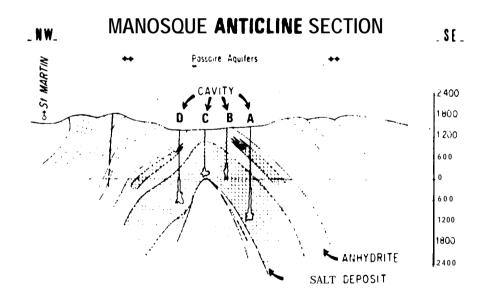


FIGURE E-4. French Hydrocarbon Storage Facility

Etzel salt deposit

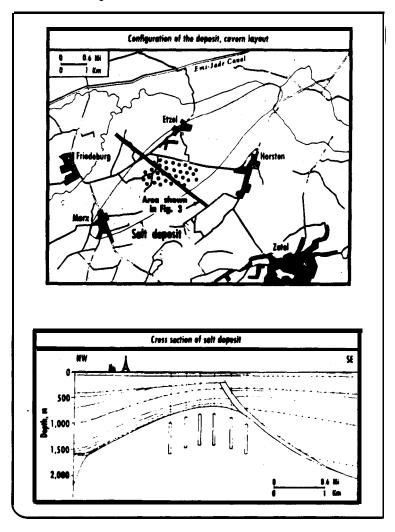


FIGURE E-5. German Crude Oil Storage Facility in Etzel Salt Dome (E-401)

storage caverns was begun in 1974. By the end of 1976, a storage volume of about 44 HUB had been leached. The leaching concept appears to be almost identical to that employed in the SPR program except that only single well leaching w&s used in the German program. This is hardly surprising mince the facility was developed by Kavernen Bau-und Betriebs-BmbH (KBB). Some of the KBB engineers and designers for the Etzel facility are now part of the PB/KBB firm, a design contractor for the SPR program. Many of the operational features for the development, filling, and crude-oil purchasing are detailed in Ref. E-40. Filling of the caverns was allowed during the construction to optimize the purchasing policies and to allow earlier use of the facilities than could have otherwise been accomplished.

Gas Producer's Association

In a recently adopted Standard [E-41], the US Gas Producer's Association set forth engineering considerations necessary for the design and construction of new underground storage chambers in which natural gas liquids will be stored. Both conventionally mined and solution mined chambers are discussed. The Standard repeatedly cites the site specific nature of a particular geologic formation as possibly leading to modification of the provisions of the Standard or changes in the original development and operational plan. It further states that a qualified engineer or geologist should perform an investigation to determine the site specific feasibility of each construction project. The writers of this Standard also recognize that chambers in current use which do not meet this Standard should not be construed as being unsatisfactory; rather, proof of design adequacy for these older caverns lies in the operating and safety experience obtained to date.

Specific requirements for the design of solution mined chambers are described below. In the design of an underground chamber, the the chamber should be isolated from zones of porosity and permeability which extend under the property of others. Casing and testing requirements include cementing from the casing seat to the surface where practicable, hydrostatic testing of the production casing, hydrostatic testing of the final cemented casing string and the casing seat, and hydrostatic testing (to the maximum operating pressures) of the milhead, cased bore hole, and storage chamber prior to product storage. The storage chambers are not allowed to extend under the property of others. Minimum separation distances between caverns should be established by considering:

1) the salt properties, 2) elevation of top and bottom of adjacent caverns, 3) their maximum development diameter relative to the spacing of the vertical bore holes, and 4) other considerations deemed appropriate for the specific site. However, separation distance may not be less than 100' unless intentional subsurface connection between adjacent caverns (i.e., a "U" tube storage chamber system) is desired. Maximum operating pressures even under abnormal conditions cannot exceed one psi per foot of overburden at either the caring seat or the cavern roof (whichever is shallowest). Minimum operating pressures are to be set by

a qualified engineer. General wellhead component and flowline requirements are cited to ensure safety and to prevent product escape.

The provisions of this Standard are in many areas intentionally vague because of the acceptance of the overriding nature of site specific geologic information and operating limitations. Never theless, the Standard clearly documents the feelings of the members of the Gas Producer's Association that site specific information must be obtained, hydrostatic testing of the casing and storage chamber is required, separation between caverns must be ensured, maximum and minimum operating pressures must not be violated, and that adequate safety in wellhead and flowline design is mandatory. The provisions of the Standard are seemingly not restricted to salt formations but have clearly been developed with considerable input from the experience gained to date in storing natural gas liquids in salt formations. The Standard does not represent a design handbook which dictates system limitations without benefit of engineering judgement but does manage to delineate major areas of concern in storage chamber design and provides aid to designers by recognizing the need for safe storage of natural gas liquids.

The only portions of the Standard which appear to require additional clarification are the requirement that cavern spacing must be at least 100' while at maximum development a cavern can extend to the property line. With these requirements, it appears that one property owner, by developing a cavern to the edge of his property, could infringe upon the neighbor's property use since the neighbor would have to be responsible for the entire 100' buffer zone between caverns. A 50' limitation to the property line would appear to be a reasonable requirement unless a joint agreement between owners is negotiated.

Comparing the SPR program with the Gas Producer's Association Standard indicates clearly that the new SPR cavern design meets or exceeds most of the specific GPF requirements. For example, cavern wall spacings for the new caverns in all cases exceed the 100' minimum set by the GPA and SPR casing seat maximum pressures cannot exceed 0.9 psi per foot of overburden (GPA limit is 1.0 psi/foot). At present, the simultaneous leach-fill concept for SPR cavern development would violate the GPA reauirement for hydrostatic testing of the solution mined chamber prior to product storage. It is well recognized that the simultaneous leach-fill operation proposed for the SPR expansion phase is a rather unique operating plan. risk associated with the simultaneous leach-fill process could be quantified somewhat by obtaining information from industry sources to define the percentage of solution mined cavities which, after completion, failed to meet certification test criteria. It is possible that this survey has been done but Sandia is unaware of the existence of a report containing this information. No comparison between GPA Standards and the SPR design of the wellhead components and flowlines is included in this cavern stability assessment.

If the GPA criteria are applied to the caverns in the ESR program, it is noted that the criteria are met or exceeded for **most** of the

chambers: however, some of the criteria are not met by certain caverns within the program. For example, the cavity spacing at the Bayou Choctaw and Sulphur Mines site will be less than 100°. The requirement for hydrostatic testing of each cavern prior to product storage was evidently followed judiciously by DOE for each ESR cavern except for cavern 115 at Bayou Choctaw. Indeed, it was this testing procedure which led to the rejection of otveral caverns tentativtly considered for crude-oil storage. In all ESR caverns, the maximum operating pressure will not exceed the CPA limitation.

Compressed Air Energy Storage (CAES) Caverns

In an effort to develop long-term stability criteria for compressed air energy storage caverns to be constructed in salt domes, Thorns and Martinez [E-42] reviewed existing rock salt literature, delineated their principal findings regarding cavity stability, and made recommendations for future investigation of the use of salt domes for CAES programs. The authors strongly emphasize that additional research work is needed to adequately investigate the unique cyclic effects of the pressure and temperatures in CAES cavern loading cycles on the progressive deterioration of casing-stat grouts and upon the response of the salt in the roof and walls of the cavern. The authors also require that the site specific utilization history of the dome in which a CAES facility is developed be thoroughly researched prior to site selection. It is also recommended that detailed studies of the geology of the salt, caprock, and surrounding formations be performed during planning stages since circulation in the caprock-salt contact zone, the presence of significant "anomalous" zones of gas pockets, weak salt, hydrocarbons, or the presence of large lateral tectonic stresses could lead to facility failure if not evaluated prior to construction. Mechanical testing of the salt, caprock, and other appropriate adjoining geologic units is also delineated. Table E-2 contains recommendations for additional CAES study. Finally, the authors recommend a program for the development of site-specific stability criteria which emphasizes at every stage of the design, the gathering of site-specific technical data, numerical modeling which leads to quantitative results and the correlation and verification of the models with the laboratory and field data. A logical design progression from performing laboratory bench scale tests, to monitoring a pilot cavern, to comparing design calculations with the results of dttailtd observations made in both prototype and, finally, production caverns is proposed.

Creep testing apparatus has recently been assembled for evaluating that mechanical response of salt specimens under CAES loading conditions [E-43]. The cores to be tasted initially will be taken from the floor of a mine in south Louisians. Long-term tests (up to six months) will be made using constant lard conditions as well as using sinusoidal variations in temperature and axial stress. Selected holes from which the cores are removed will be monitored to determine the in-situ response of the rock salt to changes in bore hole pressure, air humidity and air temperatures. The results of the mint bore hole tests will be correlated with the laboratory measurements to assess the transferability of laboratory data to field situationo.

TABLE E-2

Topics for Additional Study Relative to Long-Term Stability of CAES Caverns in Salt Domes (Thorns and Martinez, 1978)

Long-Term Creep, with Creep Rupture, of Rock Salt.

Effects of Pressure and Temperature Loading Rates.

Low Frequency Fatigue, with Coupled Cyclic Pressure, Temperature, and Wetting Conditions.

Progressive Air Penetration of Salt Fabric.

Cavern Monitoring Methods.

Correlation of Laboratory, Analytical, and Field Results.

Radioactive Waste Isolation in Salt Deposits

Salt domes, anticlines, and bedded salt deposits are currently being intensively investigated for the development of facilities for the isolation of radioactive waste products. The investigation of the potential for utilizing salt domes in Louisiana for these purposes is centered at Louisiana State University's Center for Environmental Studies [E-44]. Although this investigation is to assess the tectonic and hydrologic stability of many of the Gulf Coast domes, most of the site specific investigations are concentrated in the Vacherie and Rayburn domes. Because of the long time frames for which isolation is required, an in-depth assessment of the tectonic stability of the domes is being performed. Extensive field testing is being done using high precision leveling, laser ranging, tilt meters, recording seismographs, and vertical extensometers to assess current vertical crustal movements. These data are being correlated with finite element models to provide a validated tool for assessing the long-term movement of the domes. In addition, the deformation response of bore holes drilled in each of the domes is being carefully monitored. A microseismic monitoring system forassessing subsidence over extracted regions has been developed and is being The hydrologic studies have extensively utilized active tested. wells drilled in the two domes. Efforts have been made to map saline anomalies in the ground water around Mississippi salt domes. In a recent paper, C. Smith [E-45] indicates that less than 30 meters of salt will be removed from the upper surfaces of domes in the northeast Texas salt dome basin in 250,000 years. Thus, these preliminary studies show that even apparently unstable domes may be sufficiently stable to serve as waste disposal sites. Techniques for assessing the source and age of water which appears in active salt mines are being studied.

The development of a Waste Isolation Pilot Plant (WIPP) is being investigated by engineers and scientists at Sandia Laboratories. This project is committed to the concept of laboratory scale testing of material from potential sites, numerical simulation of mine design geometries, and verification of numerical techniques and the transferability of laboratory measurements through a comprehensive and closely correlated program of bench scale and field tests. The field tests are currently using mines in southeastern New Mexico that are in the same basin as the proposed site. Further testing is planned when the initial regions of the storage facility are opened.

In a 1977 review [E-46] of the laboratory testing, numerical modeling, and in-situ field testing efforts performed in support of waste isolation several recommendations were offered. In the area of laboratory testing, it was recommended attention be focused on evaluating long-term creep effects using both compression and extension tests. Fabric studies on deformed and undeformed specimens were recommended to assess potential deformation mechanisms and additional bench scale testing of large salt specimens was proposed. The numerical simulations were deemed to be in need of more realistic constitutive

models and more correlation studies with bench and field scale data were recommended. Field test recommendations centered upon desires to obtain failure data from in-situ studies and the reviewers noted the need for data obtained from bore hole monitoring at potential sites.

Other Related Projects and Research Programs

The most advanced project in air storage is the 290 MW plant constructed over a salt dome in Neunhuntorf, West Germany [E-42,E-47]. Two solution mined cavities (total volume 10,000,000 cubic feet) store air at 1000 psi thereby providing compressed air for about two hours of peak production capacity in their gas turbines. The caverns are 1800' deep and are cylindrical in shape with a diameter of 100' and a length of 600'. The caverns are well isolated from one another by a 722' distance and have a roof thickness of 382'.

A comprehensive laboratory and field test program [E-48] was developed and implemented under the auspices of the Civil Research Department of Ontario Hydro in Toronto, Canada, to provide rock mechanics information for optimizing the site selection for and design of an oil storage facility at a proposed thermal generating station. Laboratory test efforts included petrophysical studies, geochemical anlyses, and geomechanical tests of the limestone and shaly limestone cores taken near Wesleyville, Ontario. The geomechanical tests included unconfined compression tests, indirect tension tests, and direct Field tests were conducted to assess the transferashear tests. bility of laboratory property measurements to field usage. The field tests included a Goodman jack survey, TV bore hole surveys, cross bore hole geophysics, overcoring stress relief tests, and point load tests. Finite element calculations were made to assess the effects of the high horizontal stresses (indicated in the in-situ stress measurements) on two openings and to assess the effects of the thermal loading expected during the facility operation on the stress field surrounding the storage cavern. A comprehensive instrumentation and monitoring program is being planned for the access tunnel that leads to the proposed oil storage cavern. The information of the proposed of the The information from these measurements (made prior to final excavation of the storage cavern) will provide the final site specific data input to the final design of the cavern.

Ongoing research efforts should continually be evaluated by SFR personnel as regards their relevance to this program. In particular, the Solution Mining Research Institute sponsors research to aid in the design of solution mined cavities developed in salt formations. This research has led to the development of a computer simulation program for predicting the shape of solution mined caverns [E-49] and to improved instrumentation for mapping the edge of domal deposites and inclusions within the salt [F-50]. Additional progress is being made in SMRI-sponsored research at the University of Illinois which is concentrating upon the investigation of subsidence above a collapse feature and upon finite element simulation of cavern stability. American Gas Association is sponsoring

research at Penn State University under the direction of H. R. Hardy, Jr. This research has provided preliminary assessments of potential cavern instabilities [E-51], the development and testing of a bore hole probe for microseismic monitoring (in bore holes drilled from the surface) of the stability of geologic structures [E-52], and has outlined how the microseismic techniques can be used for monitoring storage caverns [E-53]. Recent presentations [E-54 - E-561 indicate that design criteria for salt cavity storage of natural gas are being developed with the aid of a finite element program and that acoustic emission, stress relief, and x-ray techniques are being utilized to study the response of laboratory specimens of salt. In the acoustic emission study [E-54] preliminary data have been obtained which indicate that acoustic signals are emitted by the salt during creep, dissolutioning, and during the transition from elastic to plastic behavior.

Supporting Numerical Analyses and Laboratory Testing

To aid in the technical evaluation of the needs of the SPR program, two sets of numerical simulations have been made and a limited suite of quasi-static and creep tests have been performed in the rock mechanics laboratory at Sandia. Since separate Sandia Laboratories reports have been prepared for each of these efforts [E-57 - E-591, these studies will be highlighted here and only the major conclusions will be reviewed.

Adjacent Cavern Interaction Study

As noted 'in Figures E-6-E-8, there are several caverns in the ESR program which are separated by significantly smaller pillars than would be recommended for new caverns. In addition, crude oil withdrawal by fresh water injection will further decrease the spacing between these caverns. The worst loading condition which the pillar material will see occurs when different pressures are maintained in adjacent caverns.

Two plane strain finite element models were developed (Figure E-9) to simulate both a vertical cross section between caverns and a horizontal slice between the caverns. The top of the caverns are simulated at a depth of 3200'. The height of each cavern is 600' while each cavern has a diameter of 300'. The models were analyzed for two loading conditions. In both cases, the cavern on the left (cavern A) was pressurized using the brine head while the cavern on the right (cavern B) had either an oil head (case A) or was assumed to be at atmospheric pressure (case B). Four values (2., 1., 0.5. and 0.2) of the pillar (wall thickness) to cavern diameter ratio were simulated and an elastic-plastic material representation [E-60] was selected for the salt. The deformed grid patterns (magnified substantially for ease of viewing) for the two loading conditions is shown in Fig. E-10 for P/D = 0.5. It should be pointed out that the most likely loading condition encountered in the SPR applications will definitely be case A, although it is conceivable that case B

BAYOU CHOCTAW - Iberville Parish, Louisiana

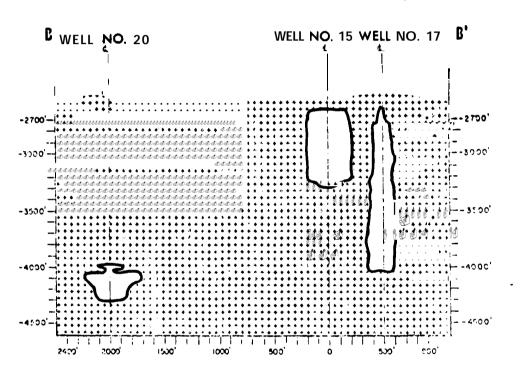
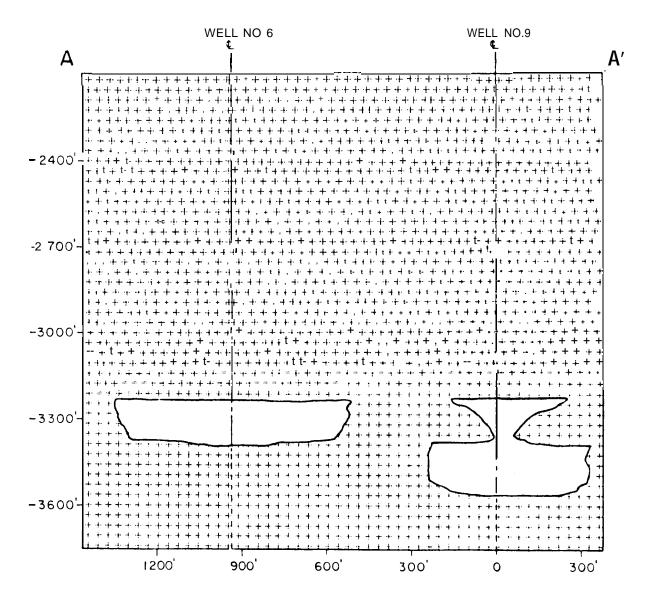


FIGURE E-6. Cross Section of Caverns at Eayou Choctaw

WEST HACKBERRY - Cameron Parish, Louisiana



FIGURF E-7. Sonar Based Profile of Caverns #6 and #9 - West Hackberry Site

SULPHUR MINES - Calcasieu Parish, Louisiana

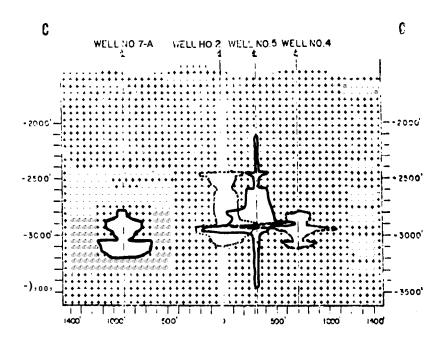
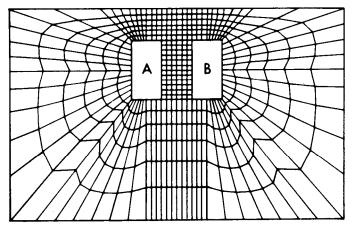
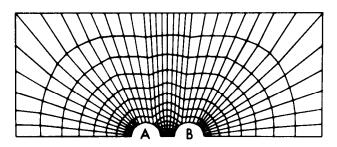


FIGURE E-f?. Crosssectron of Sulphur Mines Caverns



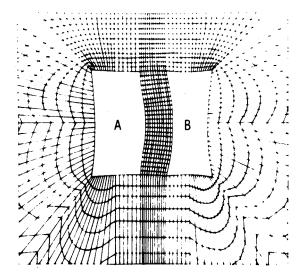
A. TYPICAL GRID PATTERNS FOR VERTICAL IDEALIZATION



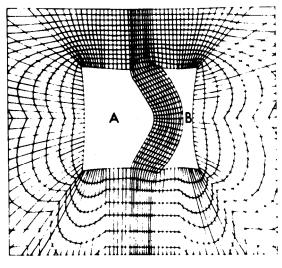
8. TYPICAL GRID PATTERNS FOR HORIZONTAL IDEALIZATIONS

FIGURE E-9 FINITE ELEMENT MODELS FOR CAVERN SEPARATION STUDY

DEFORMATIONS ARE MAGNIFIED 54 TIMES



A CAVERN B HAS OIL HEAD PRESSURE



B. CAVERN B IS AT ATMOSPHERIC PRESSURE

FIGURE • 10 DEFORMED GRID FOR P/D = 0.5

could be approached if a cavern were unable to maintain a brine head. Since the tensile strength of salt is low (100-300 psi), it is assumed that these calculations may be interpreted to indicate that in regions where tensile stresses occur, there is a potential for slabbing of the pillars. When P/D was reduced to 0.2 (Figure E-11), a tensile stress occurred in the region between the caverns in both models even when cavern B was filled with oil. When cavern B was fully evacuated, the potential for substantial slabbing was noted even for P/D = 0.5. The recommendation that similar pressure histories be maintained in adjacent caverns when P/D ratios of less than 0.5 are observed follows from this study since it is evident that slabbing potential can be minimized by keeping the same pressure in each cavern.

Closure Analysis of West Hackberry Cavern #6

A finite element analysis of cavern #6 at West Hackberry has been made to estimate the creep closure rates that were experienced during and after depressurization which resulted from the September 21, 1978 fire at this site. The cross-sectional profile of this cavern was presented in Figure E-7. In this analysis, the effects which cavern #9 might have upon the response of cavern #6 are neglected. Cavern #6 is assumed to be axisymmetric and the geometry shown in Figure E-12 was modeled using the MARC finite element program [E-61]. Since these calculations were initiated at about the same time as the laboratory testing program, site specific material properties were not available for use in the analysis. Two sets of salt data were selected from the available literature to indicate the variability of salt properties between formations and to attempt to bracket the volume change in the cavern that was indicated by the pressure measured at the wellhead. The creep response of the salt is represented by a primary creep law presented by Hansen IE-621 for salt from the Jefferson Island, Louisiana dome and from the Lyons, Kansas site. The relationship between the axial strain and the stress and time for the tests conducted by Hansen is written as:

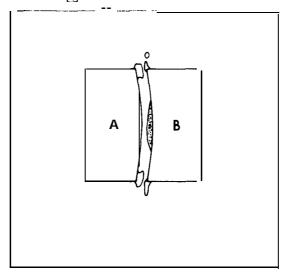
$$El = A \sigma^m t^n$$
 (E-3)

where t is the time in seconds, and σ is the differential axial stress in psi. A strain hardening form of this law was used in the MARC code. For the Jefferson Island salt the parameters in the creep law are

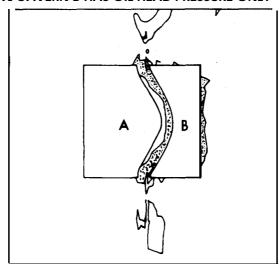
$$A = 3.4 \times 10^{-13}$$

 $m = 2.5$
 $n = 0.38$ (E-4)

REGIONS OF TENSILE STRESS



A CAVERN B HAS OIL HEAD PRESSURE ONLY



B. CAVERN B IS AT ATMOSPHERIC PRESSURE

FIGURE E-I 1 MAXIMUM PRINCIPAL STRESS CONTOURS FOR P/D = 0.2

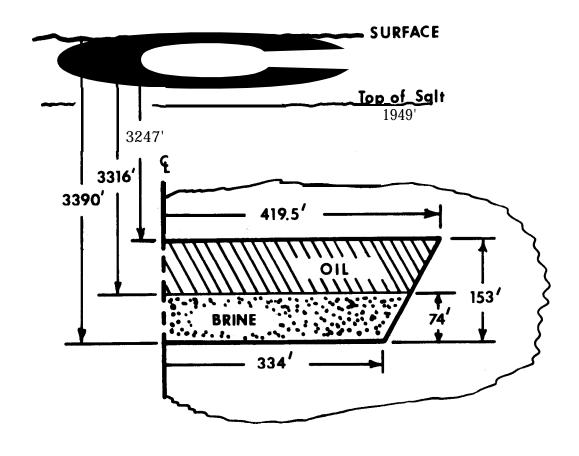


FIGURE E-12. Schematic Diagram - West Hackberry #6

The parameters used for the Lyons, Kansas salt are

$$A = 1.53 \times 10^{-15}$$

 $m = 3.0$
 $n = 0.4$ (E-5)

The finite element mesh used in this study is shown in Figure E-13. The grid contains 456 elements and a total of 507 nodes. boundaries are assumed to be at least 1200' from the center of the cavern. The loading conditions to which cavern #6 is subjected are shown in Figure E-14. From this figure it may be observed that the cavern certification loading is significantly higher than the operating pressures, line D-E-F, seen in the cavity. Furthermore, there is only a small change in pressure from the top_of the cavern to the bottom since the height is only 150'. For this analysis, the pressure variation with depth in cavern #6 is neglected. The cavern loading after depressurization is shown as line A-B-C; this loading represents a significant drop in pressure (at least 575 psi) from the operating conditions. The wellhead pressure data recorded after the cavern was depressurized are presented in Figure E-15. The pressure history simulated within the cavern is shown at the top of Figure E-16. At the start of the analysis, the pressure (line a-b) of the brine in the cavern was simulated for a period of 40 days to allow the initial, high transient creep rates to decay before simulating the depressurization of the cavern rates to decay before simulating the depressurization of the cavern. Depressurization was simulated for a period of 20 days (line c-d) Depressurization was simulated for a period of 20 days (line c-d) using the Jefferson Island salt properties. In a subsequent run, the pressure in the cavity (after 5 days of depressurization) was allowed to rise in 25 psi increments until a pressure increase of 4-500 psi was reached (line e-f). The deformations predicted for the various loading conditions are plotted in Figure E-16. For both material models, the upward motion of the floor at the center of this cavern is essentially equal to the downward displacement of the roof while the radial closure (at the midheight of the wall) is approximately one-half of the roof and floor values. The deformed profile of the cavern is shown in Figure E-17 with the displacements magnified 20 times to achieve visibility. The change displacements magnified 20 times to achieve visibility. The change in cavern volume during the time (45-120 days) in which the pressure was rising is shown in Figure E-18 along with the volume change computed (considering the compressibility of the oil and the brine in the cavern) from the wellhead pressure data for well #6B. The analyses using the Jefferson Island and the Lyons, Kansas and the properties are seen to bound the volume change computed from salt properties are seen to bound the volume change computed from the wellhead data.

These calculations demonstrate that meaningful evaluations of the response of SPR caverns can be obtained by correlating the results of numerical simulations with measured field data. Follow on efforts should obviously include repeating these calculations using material property data obtained in the current Sandia test program as well as correlating similar analyses on other ESR caverns with available field data (for example, at West Hackberry cavern

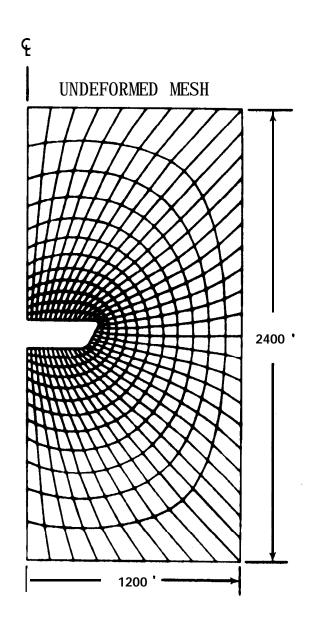


FIGURE E- 13 AXISYMMETRIC FINITE MODEL OF WEST HACKBERRY CAVERN # 6

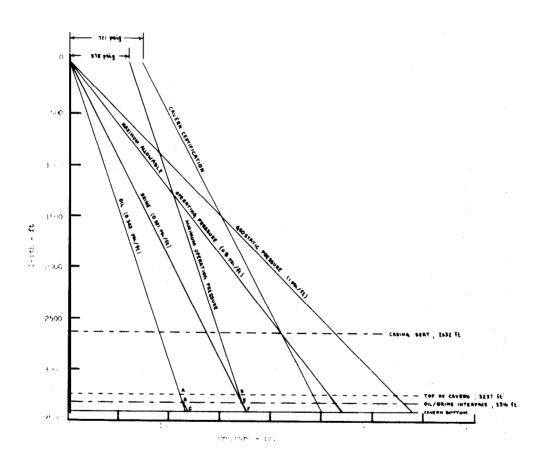


FIGURE E-14. Loading Conditions for West Hackherry Cavern #6

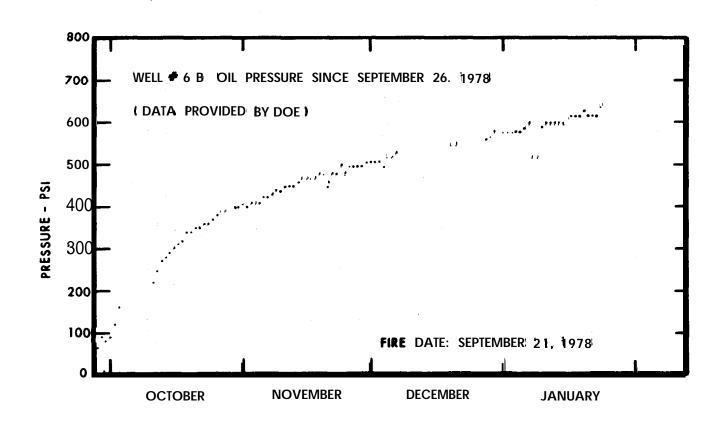


FIGURE E- 15 WELLHEAD PRESSURE FOR WEST HACKBERRY WELL # 68

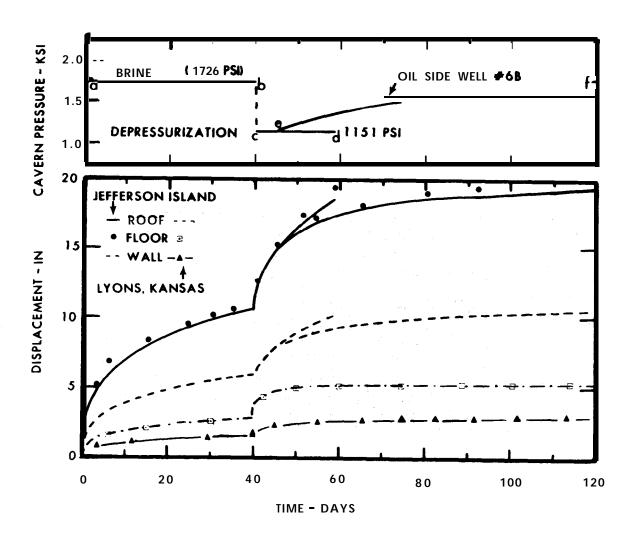


FIGURE E- 16 SIMULATED LOADING AND PREDICTED DISPLACEMENTS - WEST HACKBERRY CAVERN # 6

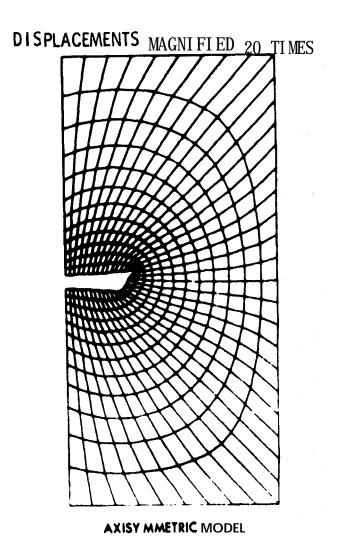
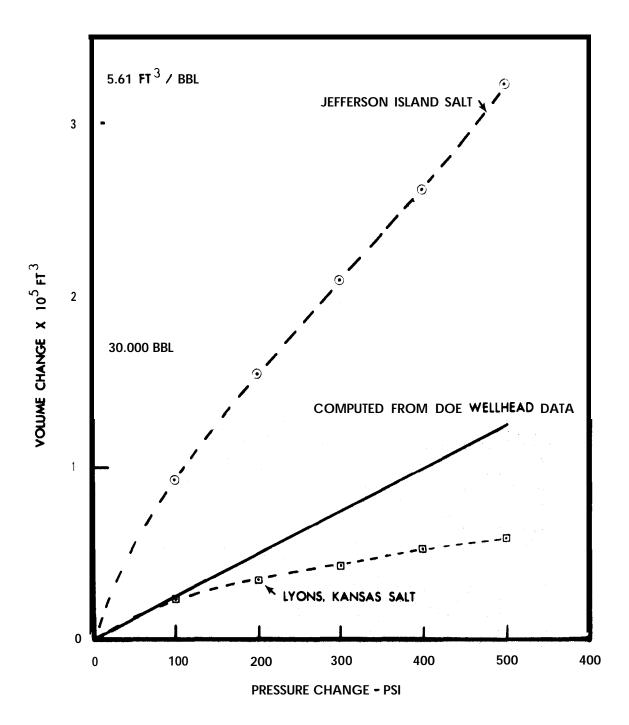


FIGURE E-I 7 DEFORMED PROFILE OF WEST HACKBERRY CAVERN #6



#11). As further confidence in the numerical simulations is developed, more accurate simulations of the projected new caverns can be made.

Laboratory Tests on SPR Salt

The quasi-static tests performed on cores from the Rayou Choctaw salt dome represent the only reported [E-22] data for the ESR solution cavity sites. To evaluate the response of the salt from the West Hackberry site, a limited suite of creep and quasi-static tests have been performed at Sandia. A complete description of the test program and the results of these tests is provided by Wawersik and Hannum in Ref. E-59. Core samples from the site were obtained from the temporary core storage facility monitored by Core Labs in Lafayette, Louisiana. The cores were machined into test specimens approximately 4" in diameter by 8" long. The creep test machines (also used for the quasi-static tests) were designed and constructed at Sandia. These rigs are capable of applying up to 10,000 psi pressure to 4" diameter samples while accurately monitoring both the axial and radial deformations of the sample. Tests can be performed at temperatures up to 250°C. These machines have been used extensively to test salt from bedded deposits considered for radioactive waste disposal [E-63 - E-641.

The test program for the West Hackberry salt was developed to attempt to bound the response of the old and new caverns. The values of the confining pressure and axial stresses were selected by considering the stresses predicted in finite element analyses of the new caverns (E-211. The temperature of 60°C was selected for the elevated temperature test since cavern temperatures of 43-60°C are anticipated [E-65] in the caverns. Unconfined compression tests at ambient temperature conditions (22°C) and at an elevated temperature (60°C) were performed. Triaxial compression tests under similar conditions were also conducted using a 2000 psi confining pressure. A triaxial extension test at a 2000 psi confining pressure and at 22°C was also completed. Creep tests in both triaxial extension and compression were run using a confining pressure of 2000 psi and a stress difference of 3000 psi for both ambient and elevated temperature conditions.

The ambient temperature unconfined compressive strength of the West Hackberry salt is compared with that of salt from other deposits in Figure E-19. The secant modulus computed for the West Hackberry salt is similarly compared with other salt in Table E-3. The temperature dependence of the salt was noted in the quasi-static tests since the strain to failure in both the unconfined and triaxial tests for the 60°C tests was nearly twice the values measured at ambient temperature (22°C). Some of the quasi-static test results are shown in Figure E-20. The results of creep tests performed at ambient temperature and at 60°C are compared in Figure E-21 where it is observed that significantly more axial strain occurs in the heated case than in the ambient temperature test. The results of the ambient temperature test are compared in Figure E-22 with Jefferson Island and Lyons, Kansas data. In this comparison, the creep response of the West Hackberry salt is

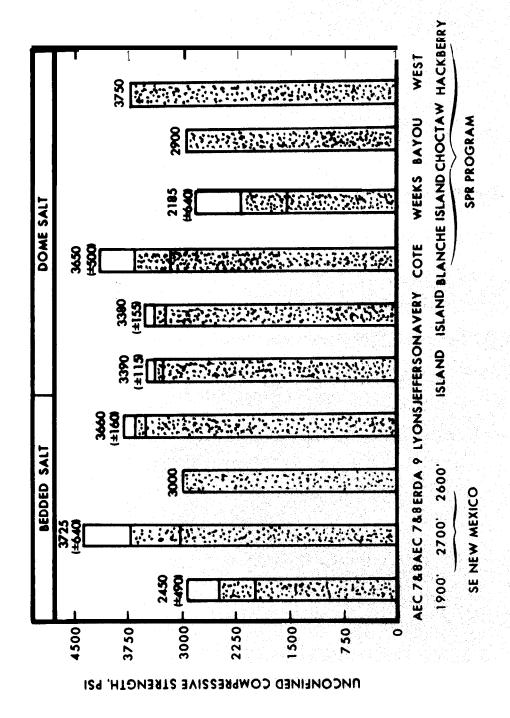


FIGURE E-19 COMPARISON OF UNCONFINED COMPRESSIVE STRENGTHS FOR BEDDED AND DOME SALTS

TABLE E-3

Average Moduli of Deformation for Salt From Various Locations in the U.S.

SITE	SALT TYPE	SECANT MODULUS ^a (10 ⁶ psi)
Lyons, Kansas	Bedded	0.87 <u>+</u> 0.31
Southeastern New Mexico	Bedded	0.57 <u>+</u> 0.20
Jefferson Island, Louisiana	Dome	0.42 <u>+</u> 0.09
Weeks Island, Louisiana	Dome	0.38 <u>+</u> 0.11
Cote Blanche, Louisiana	Dome	0.46 <u>+</u> 0.05
Bayou Choctaw, Louisiana	Dome	3.35 <u>+</u> 0.92 ^b
West Hackberry, Louisiana	Dome	0.33

- a. Values of modulus were calculated from triaxial compression test data by taking a straight line measurement over an approximately linear **portion** of the stress-strain curve, usually between differential stress levels of 500 and 2000 psi. All calculations utilized data from the **initial** stress application, not from cycl ic stress applications.
- b. Deformation modul: for these tests were computed differently than in other references.

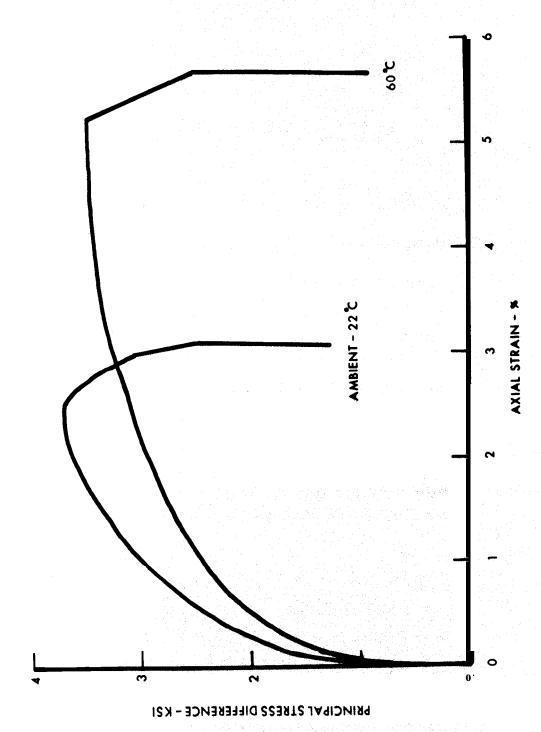


FIGURE E-20 QUASI-STATIC TESTS ON WEST HACKBERRY SALT

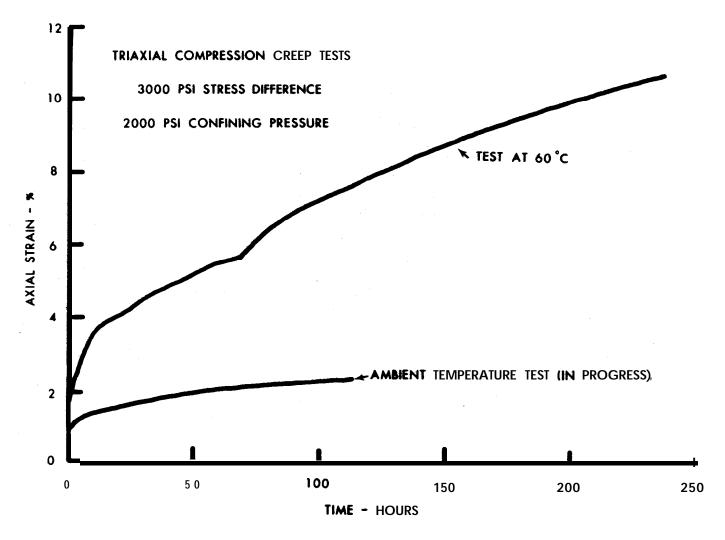


FIGURE E-21 CREEP TESTS ON WEST HACKBERRY SALT

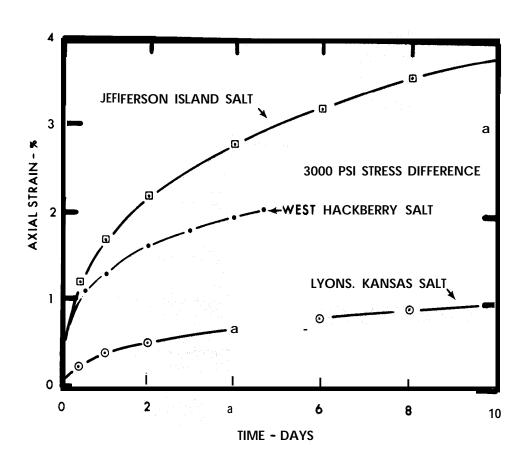


FIGURE E-22 COMPARISON OF SIMILAR CREEP EXPERIMENTS ON DIFFERENT SALT

bounded by the two reference data sets that were used in the simulation of the behavior of cavern #6 at West Hackberry. As noted previously, the analyses of this cavern likewise bounded (using constitutive models for the two reference salts) the volume change informaton gathered from the wellhead pressure measurements,

Evidence of the strong dependence of the salt behavior on temperature is also provided in Table E-4 (reproduced from Ref. E-62) which shows that a power law dependence with an exponent of 9-10 is common for Lyons, Kansas, and southeastern New Mexico salt. The data to which the West Hackberry salt have been compared are provided [E-62,E-66 - F-701. In addition to these data, excellent reviews of salt properties and their use have been prepared by Dswson [F-75], Dames and Moore [F-73], Carter [E-74], and Baar IF-751. The data presented here and in the previously mentioned references clearly establish two points. First of all, there is significant site-to-site variation in creep response. Secondly, salt response is nonlinearly dependent upon both temperature and the applied stresses. This establishes the need for a coordinated test program for determining the properties of the salt from each SPR expansion site and indicates that the test parameters must span the anticipated ranges of both stress and temperature.

TABLE E-4

Empirical Power Laws for Transient Salt Creep [E-62]

SITE	POWER LAW*	COMMENTS I
Lyons, Kansas	$\mathbf{\ell}_1 = 1.1(10^{-38}) t^{0.3} \sigma^{3.0} T^{9.5}$	Converted time to seconds
Lyons, Kansas	$\mathbf{\epsilon}_1 = 5.1(10^{-39}) t^{0.4} \sigma^{3.0} T^{9.5}$	Converted time to seconds and temperature to ^O K
S outheastern New Mexico	$\mathbf{\epsilon}_1 = 1.7(10^{-39}) t^{0.48} \sigma^{2.7} T^{10.2}$	Differential stress not corrected for strain
Southeastern New Mexico	$\epsilon_1 = 1.1(10^{-35}) t^{.47} \sigma^{2.5} T^{9.0}$	Differential stress corrected for strain

t = time (sec)

 σ = differential axial stress (psi)

 $T = temperature (^{\circ}K)$

Cavern Stability Evaluation

As mentioned before, this cavern stability evaluation relies heavily upon the work completed to date on the SPR program, the comparison of the SPR efforts with those of similar programs, and the supporting studies performed as part of the technical evaluation efforts. It is the purpose of this section to summarize the conclusions obtained through each of these areas of investigation. Although **some** site (and in many cases cavern) specific recommendations are made in this section, the succeeding section will draw from this evaluation to make general recommendations regarding cavern stability efforts needed as the SPR program proceeds.

This discussion will be divided into three parts. The first part will describe the existing (ESR) caverns: the second part will comment on the new cavern design; the last part will tie the first two areas together in a discussion of the overall SPR program.

Existing ESR Storage Caverns

While it is probable that some of the countries listed in Table E-l utilized some existing caverns for at least part of their petroleum reserve storage, the most obvious contrast between the SPR program and the storage projects mentioned previously lies in the fact that each of the other projects will use only new caverns developed specifically for the purpose of that project, i.e., no caverns created by brining operations are mentioned. This observation should not imply that the ESR caverns are regarded as unsuitable for crude oil storage. Rather, it should indicate that if existing cavities are to be used, extensive engineering studies and testing should be performed since there is only a rather limited existing data base which can directly support the selection of appropriate cavities. Put another way, if it is desired to use existing caverns to circumvent the long lead time and high costs associated with leaching new caverns, considerable effort must be made to ensure the suitability of the existing caverns for long term storage. Indeed, this has been the goal of the SPR in this program. In the first section of this report the testing and analysis work done to date for ESR storage was described. This work most adequately addressed and assessed many of the aspects of cavern stability evaluation. For example, the certification documents and the previously described stability assessments establish that there are few stability worries associated with the caverns in their current shapes when the brine head is maintained in all caverns. However, more work remains to be done to expand the data base for both cavity selection and certification (i.e., additional efforts could lead to more useful cycles for certain cavities) and for cavern operations (establishing cavity closure rates, depressurization effects, and failure criteria).

To facilitate a discussion of the ESR caverns, Tables E-5-E-8 have been compiled to show pertinent parameters for both the

TABLE E-5 GEOMECHANICAL DATA AND RECOMMENDATIONS FOR SPR CAYERNS AT BRYAN MOUND SITE

	Comments and Recommendations	Close to cavern #4. Recomend storing of same crude oil types in these 2 caverns at all times, sonar surveys after each cycle, and similar pressure profiles in each cavern when web thickness becomes less than 100'.	Relatively low B/D ratio leads to recommendation that depressurization effects be assessed through both numerical simulation and field measurements. Potential for coalescence with cavern 3 shoull be evaluated.	Large vertical separation between caverns 3 and 4. Close to cavern 1: see recommendations for cavern 1.	A shale stringer may exist in the hourglass section of this cavern. Recommend that additional efforts be expended to determine the material in this region and to assess potential effect of a stringer on stability of the hourglass section of material and plausibility of stringer leading to communication with cavern #3. Ceiling trap (1.3 mmb) in lower chamber may be minimized by directionally drilled reentry well.	Cavern appears to be self-leaching with communication with the caprock. Scope of work to investigate specific aspects of this cavern has been prepared by FB/KMB. Recommend funding of study which evaluates fresh water source, local geology, cavern leaching rates and direction and local subsidence by than exists in current plans. The potential for establishing communication with caverns 2, 4, or 5 shouls be more adequately defined. Recommend that no surface facilities or pipelines be established in cavern 3 zone of influence.
_	E/D	^	3.42	2008	2-32	
_	Distance to Dome Edge, E	ኢ	2000	2300	1700	
_	g/b	2.75	4ς•	1.89	1.36	
_	Roof Thickness, B	1209	314	1419	\$	
_	α/a	.50	.51	.29	9	
_	Distance ^c to Nearest Cavern, P	220	300	220	33†	
_	Mearest Cavern	ካ#	#3	#1	en Laka L <mark>≢</mark> e en <u>ka</u> lle belekte tit	
	. α/н	i.8,	38	ħ	1.21 ⁸ .70 8	
_	Cavern Height, H	1465	220	553	595 ⁸ 515 ⁸ 1155	
α	Cavern Diameter,	O††	A	672	491 ⁸	
_	Bottom of Cavern	4.82	1670	3108	3582	
4	Top of Cavern	2345	1450	2555	2130	
THS	Casing Seat	1476	1451	1918	2161	
DEPT	Top of Salt	1136*	1136*	1136*	1136	1136*
_	Top of Caprock	* 089	680 *	. 089	* 089	*089
_	Lype of Oil	Sweet	Sweet	Sweet	Sweet	
_	Oil Stored (mumb)	5.9	0.9	8.4	12.5	
_	Volume (mmb)	9.9	5.9	16.3	33.3	
	Year Constructed	1943	1957			
_	Cavern Number	-	2	7	ιr	<u>م</u>

* For of papers, unical repths are estimated; this information will be determined for other areas in the dome as part of the expansion well smilling program.

A favorable has two leves one on top of the other) which provide an hourglass shaped cavern. The diameter of the lower lobe is used to determine the PC, BC, and it is notice.

[.] This enverome is not in the EGR program but has a potential impact on ESR caverns. We Then All distances are given in feet.

TABLE E-6 GEOMECHANICAL DATA AND RECOMMENDATIONS FOR SPR CAVERNS AT WEST HACKBERRY SITE

	Comments and Recommendations	Longest flat roof span in single cavity in ESR program. Recommend defects through numerical simulation and fleld testing to monitor well head pressures and flow volumes to achieve selected pressure drops. Recommend sonar survey to determine if roof falls occurred during or after the fire. GIEC recommended additional investigation or assessment of edge of dome.	Only cavern at West Hackberry in which sweet crude is currently stored. Top 600' is cylindrically shaped; lower 350' is spherical. Well isolated from top of dome and nearby caverns.	Will coalesce (after 3 cycles) with cavern 9. Recommend maintaining the same crude oil type in each cavern, sonar surveys after each cycle, and similar pressure profiles in each cavern when web thickness becomes less than 100'.	Will coalesce (after 3 cycles) with cavern 8. See recommendations above.	Recommend numerical simulation of creep closure and close monitoring of well head pressure and brine flow since this cavity represents almost a perfect prototype of the planned expansion cavities (i.e., cavity is cylindrically shaped with 306' maximum diameter while new cavities will have 270' maximum diameter). Cavern is well removed from the caprock, dome edge and other cavities.
	E/D	.83	>2.33	×2.24	NA*	>3.27
	Distance to Dome Edge, E	700	>1000	1.01 >1000 >2.24	*AM	>1000
	a/a	1.54	1.34	1.01	1.8	2.91
8	Roof Thickness,	8821	577	644	1057	698
	σ/4	£.	1.63	æ.	27	ř.
a	Distance to Mearest Cavern,	315	700	160	160	>1000
	Mearest Cavern	6#	9#	6#	#8	
	а/н	.18	2.22	2.27	.60	2.66
_	Cavern Height, H	153	956	1011	351	815
α	Cavern Diameter,	839	430	3	288	306
	Bottom of Cavern	3395	3498	3451	3561	3760
ェ	Top of Cavern	3237	2542	2440	42£	2945
E	Casing Seat	2632	2400	3,	⁸ را	2790
	Top of Salt	1949	4	1991	2153	2056
	Top of Caprock	4	1551	1515	1550	1529
	Type of Oil	Sour	Sweet	Sour	Sour	Sour
•	(dmmm) berota Lio	6.9	2.8	0 2	2.3	6.5
-	Volume (mumb)	12.2	12.3	10 1	8.9	8.5
	Year Constructed	1346	1946	1946	1947	1962
		9	7		6	11

x - x , applicable since another cavern is between $\#^0$ and dome edge.

NOTE: All listances are given in feet.

TABLE E-7 GEOMECHANICAL DATA AND RECOMMENDATIONS FOR SPR CAVERNS AT SULPHUR MINES SITE

S		_	_				DEP1	iHS ·	- fr		A				•	_		_			
U L P H U	Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Type of 011	Top of Caprock	Top of Salt	Casiny Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter,	Cavern Height, H	а/н	Nearest Cavern	Distance to Mearest Cavern, E	α/a	Roof Thickness, E	a/a	Distance Dome Edge, E	E/D	Comments and Recommendations
R	2	1946	6.2	*	*	500	1460	15%2	2447	3086	400	635)			4 2		<u>≈</u> _	2.4			Caverns 2-4-5 have already coalesced.
M	4	1949	2.9	*	*	819	1620	1610	2793	3115	420	322	.77				1173	2.7	364'	.87	Total storage volume in the 3 cavities is 12.3 mmb. Solution channels exist
I N E S	5	1953	3.3	•	*-	829	1480	1714	2448	3450	220	1002	¥.55	Allied #2 Well PPG #1-A	380' 250	.6;	961	ηη ι		1	between 4 and 5 at 2000' and between 2800-2900' for caverns 5 and 2. Recommended for only 2 cycles of use. Distance from cavern 2-4-5 gallery to 6-7 gallery is 310'. Major diameter for 2-4-5 gallery is 1140'; minor diameter is 585'; maximum height 1002'.
																					The jagged cavern profiles clearly indicate layer of highly soluble material. Recommend surveys on Allied #2 well and FPG #1-A to firmly establish proximity to 2-4-5 gallery and agreement regarding future production plans to ensure no interference with ERR storage. Recommend creep analysis of 2-4-5 gallery to assess depressurization effects. Recommend same crude types be stored in all Sulphur Mines cavities. Assessment of potential for fracturing of cavity ledges during filling, withdrawal, and depressurization should be made; similarly potential for damage to brim strings (and ensuing delivery delay.) should be made.
	6	1955	5.1			620	1470	1836	2968	3401	618	433	.70	#7	100'	.16	149€	2.4:	33 ^a 50 ^b	.73	Because of their closeness, caverns 6 and 7 will be treated as a single gallery. Unusual shape have long radii alternating with small diameter necks. PS/KBB edge of dome study used current drill hole information to estimate distances. These data are not in complete agreement with previous studies.
	i	1957	5.6		•	962	1500	1855	2790	3195	497	405	.81	#6	100'	.20	1290	2.6	35 ^a 80 ^b	.47	Proximity to dome edge represents greatest potential for storage product loss especially since solution mining is continuing. Recommend additional investigation through test drilling program for the 6-7 gallery; study could potentially lead to more than 1 cycle certification. Recommend maintaining similar pressure profiles in 6-7 gallery to minimize pillar slabbing potential. Recommend that edge of dome investigation be completed prior to product storage.

^{*}No oil is currently stored at the Sulphur Hi--- site.

General Site Comments - The presence of highly soluble lenses of material is somewhat unusual in Gulf Coast domes. Predictions of cavern enlargement should consider these high soluble regions. The uncertainties regarding the location of dome boundaries, the lack of operating experience with a cavity of the size of the 2-b-5 gallery, and the potential for slabbing of ledge material mandate that careful consideration be given to establishing operating procedure, which will minimize Potential withdrawal problems or delays and necessitate additional geotechnical work to assess the viability of failure scenarios. This is the only site currently considered in the ESR program in which additional caverns may be developed by other than SFR personnel below the storage caverns. An easement would permit construction below 4000' but would prohibit spans greater than 500', distances between cavern walls of less than 200' and cavern roofs flatter than 30 from the horizontal.

NOTE: All distances are given in feet.

^{8.} Distance given in site certification document.

b. Distance given is site report by PB/KBB.

TABLE E-8 GEOMECHANICAL DATA AND RECOMMENDATIONS FOR SPR CAVERNS AT BAYOU CHOCTAW SITE

ESR	Stor	y Cav	erns	L		-	DEP	rhs ·	- h		A	d			, ما		۱ ۴			ı	
A Y O U	Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mamb)	Type of 011	Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter,	Cavern Height, H	Ф/н	Nearest Cavern	Distance to Mearest Cavern,	a/a	Roof Thickness,	B/D	Distance to Dom	E/D	Comments and Recommendations
SP100H0	15	1953	15.7	11.6*	Sour	477	6 37	2560	2597	297	350 480 ^a	700	2.0	17	57-100'	.1629	2000	5.71	≻6 α		Not certified or pressure tested by DOE. Extremely close to cavern 17 which contains ethane @ 2000 psi. PB/KBB recommended limit to 1 cycle unless cavern 17 is obtained or operational agreement is signed. New survey of cavern 17 is recommended. Recommend development and implementation of certification plan (including review of previous tests) for cavern 15 and pursuance with utmost haste agreement concerning (or purchase of) cavern 17. Until this work is completed, recommend "o fresh rater withdrawal, no intentional depressurization, and close monitoring of well head info.
	18	1967	8.5	3.8*	Sour	430	850	1176	2110	240	385	:130	5.53	17	380	-99	1260	3.27	784	2.03	This cavern could potentially be effected by uncontrolled leaching of cavern 17.
	19	1967	7.5	5.1*	Sour	550	850	2305	2995	1270	264	1275	4.83	16	450	1. 7	214:	8.1	50	1.89	Certified as usable for 5 cycles pending information obtained regarding current. shape of cavern 16 and future operational plans.
	20	1970	5. 2			500	680	1085	3980	4306	525	380	.72		NONE CLO		3299	5.2	135	.26	Close proximity to dome edge will preclude more than 1 fresh water cycle. Recommend additional assessment of dome boundary (possibly including drilling program) and Close monitoring of well head pressure and flow information during and after filling.

^{*}Oi:1 stored as of 2/12/79.

General Cite Comments - Poor quality, thin caprock (mostly gypsum) exists at this site. Major drilling problems were experienced due to loss of circulation neal salt/caprock interface and presence of gas in salt-caprock interface. Additional costs and delays should be anticipated at this site for drilling reentry wells and expansion wells.

NOTE: All distances are give" in feet.

a. Diameter used in SAI cavern stability study.

TABLE E-8 (CONT.) GEOMECHANICAL DATA AND RECOMMENDATIONS FOR SPR CAVERNS AT BAYOU CHOCTAW SITE

	tional (u Chocte			_		ı	DEPT	HS ·	- ft		A					_					
Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Post of 241		Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cerern	Cavern Dismeter,	Cevern Height, H	H/D	Hearest Cavern	Distance to Hearest Cavern,	σ/a	Roof Thickness,	B/D	Distance to Dome Edge, E	Z/D	Comments and Recommendations
2*	1934	6.0			3	76	639	751	751	1560											Originally certified by GIEC for limite- use but now rejected. Thin roof (<100' implies marginal stability. Concur with recommendation to locate no surfac- facilities above this cavern. Impacts the construction during expansion phase of cavern 102 since directionally drilled wells would be required if current expansion layout is used.
1,*	1935															•		-			No salt roof in cavern. Self-leaching cavern enlarged between 1963 and 1977 surveys. PR/MEB recommended yearly sonar surveys and semiannual subsidence monitoring. No surface facilities should be placed above this cavern as it has a relatively high probability for collapse.
8*	1944	2.9			4	32	776	1161	1243	1975	150										Potentially useful for oil storage if washed out area near casing can be sealed. Efforts to seal cavity not successful in 8/18/78.
16*	1953	8.5									255 360	600									Used for ethylene storage by Allied. PB/KBB recommended sonar survey and directional well survey. Operational plans for use of this cavern should be obtained.
17*	1955	11.5									200 295	1445									Owned by Allied. Ethane stored at 2000 psi. Significant potential for interaction with cavern 15 which can result in loss of product quality. Concur with HB/KEB recommendation for obtaining new surveys and operating information. See recommendations regarding cavern 15.
1	1937	8,1		L	4;	15	653	951	1028	1808	2:35										Cavern rejected because of lack of pressure tightness.
3	1925	3.9			50	×6	660	1008	1008	1873	295										Cavern rejected because of communication with 11, 13 and caprock.
6	1943							. :													Small cavern with high magnesium con- tent. Allied is enlarging for product storage.
7	1942				Τ																Collapsed in 1954 forming surface lake.
9	1944				Γ																Local subsidence resulted in abandon- ment.
10	1947																				Mear west flank. Loss of pressure tightness indicates possible casing lead or communication with dome edge.
11	1747	7.5		Ŀ	Non	e	704	951	1080	1752											Rejected because of communication with 3, 13 and caprock.
13	1948	4.3			57	1	875	1112	1115	1882											Cavern rejected because of communication with 3, 11 and caprock.

^{*}Caverns which have highest potential for significant impact on SPR program. These caverns are not currently being used for crude oil storage.

a. Limensions used in SAI Cavern Stability Report.

NOT: All distances are given in feet.

caverns in use (or planned for use) at each site (Bryan Mound, West Hackberry, Sulphur Mines and Bayou Choctaw) and, in some instances, for other caverns at the sites which might impact the use of the existing caverns or the construction of new ones. The tables show that the cavern volumes range from about 3 MMB to more than 33 MMB. The heights vary from 153' to 2130'; diameters range from 220' to 839'. The tops of the caverns are from 1450' to 3980' below the surface while maximum depths are between 1670' and 4306'. The cross-sectional views of the caverns shown in Figures E-6-E-8 demonstrated clearly the variations of these caverns from regular shapes, i.e., from cylinders, spheres, ellipsoids, etc. Since the cavern geometry as related to the distance (both vertically and horizontally) to the dome boundaries and to adjacent caverns governs in large part the suitability of a cavern (from a geomechanics viewpoint) for storage, these properties and ensuing ratios to the cavern diameter have been recorded for each ESR cavern (Tables E-5-E-8). The data presented in these tables were obtained primarily from the cavern certification documents [E-5-E-19] and from other SPR contractor generated documents [E-2-E-4, E-20-E-24, E-30,E-77]. In several instances the cavern properties (diameter, height, depth, spacing, etc.) reported in these documents, particularly in Ref. E-20, differed substantially from one another. In these instances, the values reported are either those of the certification documents [E-5-E-19], the values from the as built drawings [E-77] or those from the more recent reports by PB/KBB [E-21, E-221.

The distance between adjacent caverns, P, is the current wall thickness (not center to center spacing between caverns). This value can be used as a measure of the likelihood for cavern coalescence and for comparison purposes with the standards set by the state of Louisiana [E-78] and the Gas Producer's Association [E-41]. The P/D ratio indicates the pillar width relative to the cavity size and is inversely related to the intensity of the loading which might be felt in this pillar, i.e., a 100' pillar between 500' diameter caverns (P/D = 0.2) would be more intensively loaded than would be the case if the surrounding caverns at the same depth had only a 100' diameter (P/D = 1). A cavern separation distance of 200' is required for new caverns in the Louisiana regulations while the GPA standard is set at 100'. In their current configuration, Sulphur Mines caverns #6 and #7 and Bayou Choctaw caverns #15 and #17 do not surpass the GPA standards (i.e., the current separation distance may be less than or equal to 100'). Furthermore, caverns #8 and #9 at West Hackberry are only 160' apart and thereby fail to meet the Louisiana standard for new caverns. For this reason, it is recommended that the same type of crude oil be stored in these adjacent caverns, that similar pressure histories be maintained in the caverns and that coalescence be anticipated if fresh water cycling of the oil is to be done at these sites. same type of oil is currently being stored in the West Hackberry caverns and is planned for the Sulphur Mines caverns. significant problems which can be anticipated with continual dissolutioning (cycling of oil or intentional cavern expansion) are in relation to caverns #15 and #17 at Bayou Choctaw because: 1) the pillar size is the smallest in the ESR program, 2) there is a resulting low P/D ratio, 3) cavern #15 has not been recently

surveyed (i.e., no certification tests or surveys were performed by DOE), 4) ethane is stored in cavern #17, and 5) there is no working agreement with Allied (owner of cavern #17) regarding the operation of this cavern. The Department of Energy reported [E-76] in 1977 that they had negotiated an agreement with Allied Chemical Corporation to acquire cavern #15 that Allied was using to store number 2 fuel oil. This cavern had previously been certified by Allied as usable for hydrocarbon storage as a result of high pressure testing. Cavern #15 and the 371,340 BBL of fuel oil it contained were acquired on December 9, 1977 and fill began on December 10. DOE did not pressure test or survey this cavern after purchase. No withdrawal via fresh water injection is recommended for cavern #15 until the cavern is certified (special plans for testing and surveying an oil filled cavern will be required) or at least until a working agreement (more preferably cavern purchase) is cotained with Allied and a survey of cavern #17 is obtained.

The roof or back thickness, B, (amount of salt between cavern roof and the caprock) is important from a cavern tightness point of view since adequate salt thickness must be present to ensure that the casing can be properly grouted. In most instances the casing seat is not grouted al 1 the way to the top of the cavern since roof slabbing or creep deformation at the center of the cavern could possibly damage the seal. From Tables E-5-E-8 it is noted that tre minimum roof thickness for the caverns in the SPR program is 3.41 (Cavern #2 at Bryan Mound). The casing extends to the cavern roof in this cavern. The B/D ratio provides an indication of a t!.ickness to span ratio for the cavern roof. In a way, this provides the geometry for thinking about the roof material as either # beam or a circular plate. As the B/D ratio decreases to well be ow 1.0, concern intensifies regarding the adequacy of the roof raterial to transmit the loads from the caprock to the cavern wa!ls without developing tensile stresses in the roof material, Cavern #2 at Bryan Mound also possesses the lowest B/D ratio, 0.54, of the storage caverns. Since the cavern is rather stallow (top of cavern - 1450'), large amounts of creep closure tue to roof motion are not anticipated during either storage or depressur ization. However, since casing damage could conceivably occur from either slabbing of weakened roof material or from small (negligible as regards cavern volume change) amounts of cread closure, a cavern specific numerical simulation of this cavern should be made to assess the possibility of casing seat damage.

Roof trickness problems in caverns #2 and #4 (these caverns are not in the SPR storage) at Bayou Choctaw have an impact on the SPR program. Cavern #2 was originally certified by GIEC for limit. d use but has now been rejected since a thin roof (less than 100' indicates marginal stability. For cavern #4 there is evidently no silt in the roof and cavern enlargement between 1963 and 1977 surveys indicate the cavern may be self-leaching. Since the four recorded cases of collapse features above Gulf Coast salt domes

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cycles in which fresh water can be used as the displacement fluid to either one or two unless additional drilling is done to more accurately establish the dome edge location relative to the cavern. Accurate monitoring of well head pressures should aid in detecting any unexpected pressure drop which might signal the initiation of communication with the edge of the dome. The use of the Sulphur Mines site is severly restricted by the closeness of the dome edge to cavern #7; this is also compounded by what seems to be regions of salt which leach faster than surrounding areas (Figure E-8). These have led to irregular wall profiles. A more accurate assessment of dome boundaries should be attained prior to crude-oil storage.

Cavern #11 at West Hackberry offers a rather unique opportunity for the SPR program. The cavern is well isolated from adjacent caverns, the top of the salt and the dome edge. Geometrically it is essentially a right circular cylinder with about a 306' diameter and an 815' height. Since the new caverns will be of an almost identical shape (diameters of 230'-270'), cavern #11 can in many ways be considered to be a prototype of the expansion phase. Head well flow rates and pressure histories should be able to serve as field data useful in enhancing the data base upon which the cavern design will proceed into the expansion phase within this dome.

If a cavern is currently stable, and has adequate salt in the roof and wall areas, the two major factors which may degrade the existing stability are the loading changes which would result from cavern depressurization and the continual dissolutioning (cavern enlargement) which accompanies each cycle of oil usage from the cavities. The loading resulting from oil storage in the cavern does not, in general, differ radically from the pressures exerted in the cavern walls when a static brine head is maintained (differences are maximized in deeper caverns). If by accident or design (possibly for casing repair or well workovers), the pressure on the oil column is reduced to nearly zero, the cavern pressure is reduced to that of just the oil head. For some of the existing caverns depressurization may be a particularly crucial loading condition since large roof spans (Tables E-5-E-8) are noted in some caverns in the storage program. In a recent rock mechanics review [E-79] of potential depressurization effects, "It was the unanimous consensus of the participants at that meeting that depressurizing the caverns could result in major problems." Cycling of the oil will lead to additional dissolutioning and thus larger caverns or, in some cases, to coalescence with other caverns. For caverns in which the original geometry is already regarded as critical, this dissolutioning may result in a limitation on the number of cycles for which a cavern is certifiable or possibly to stability concerns regarding these caverns. In general, the depressurization effects and the decreased stability resulting from crude cycling are two important problems which warrant further assessment.

SPR Expansion Phase Caverns

The new storage cavity complexes created in the SPR expansion phase may be contrasted with the design LOOP project [E-37], the West German

storage facility at Etzel [E-40, E-801, and the French program at Monasque [E-39] by observing Table E-9. From this table it is noted that the SPR caverns are very large (initially 10 MMB) compared to the other projects. When contrasted with the German program it is noted that this increase in size comes from doubling the 106' diameter used in the Etzel caverns. While the depths of the German and US caverns are similar, it may be noted that the spacing ratio, P/D, in the German complex varies from 4-7 while the anticipated initial ratio in SPR caverns is only 2.3. final (after 5 cycles) P/D ratio in the SPR caverns will average about 1.8 although locally the values range from 1.5 to greater than 2.1. The P/D ratio is similar to the 2.0 ratio proposed for the LOOP project; however, the bottom of some of the SPR caverns will be at more than twice the depth of the LOOP chambers. The simultaneous leach-fill process proposed for SPF has evidently been used successfully at Ftzel. The highly irregular wall profiles noted in the French project are not anticipated in SPR since the French facility is located in an anticipal deposit which has both large chunks of insoluble anhydrite and some highly soluble lenses of material. These conditions are not anticipated to be manifest to this extent at the SPR expansion sites but further testing of the dissolutioning rates is necessary before construction of the SPR cavities begins. Finally, it is noted in Table E-9 that only the US program will use the 3 well leaching concept.

Published documentation which supports the selection of the P/D ratio for the US caverns consists primarily of a series of creep analyses [E-21] performed at the University of Illinois. The se analyses predict that minimal amounts of radial closure should occur (less than 10" in 40 years). These analyses should be considered as preliminary since they are based upon a primary creep law fit to ambient temperature test data on salt from a Mississippi salt dome. No correlation of this law with the field data from existing ESR caverns has been reported. Furthermore, the effects of plausible variations (from the assumed hydrostatic conditions) in the in-situ stress field have not been evaluated. In the leach analysis reports for the West Hackberry [E-81] and Bryan Mound [E-82] sites, it is stated that "first estimations of the rock mechanical experts favor a P/D ratio of at least 1.2". No documentation of this statement is provided and no references are made to documents which show how this estimate was obtained. In the West Hackberry report, the text discusses the use of 330' pillar widths for 270' diameter caverns (P/D = 1.22) while the cover letter indicates that the recommended design layout will use caverns spaced 750' apart (center to center) giving a P/D ratio of 1.8. No comments are made in these reports regarding the selection of this ratio of 1.8.

In a study [E-38, E-831 undertaken for the LOOP project, the results of multi-cavity analyses are presented for various P/D ratios which predict that at a depth of 2500' caverns with a P/D ratio of 2.0 might experience approximately 10% radial closure in less than 30 years. Conclusions drawn in this study [E-38] are that

TABLE E-9 COMPARISON OF CRUDE UK STORAGE FACILITIES IN SALT FORMATIONS

Storage Program	Number of Caverns	Cavern Volume (mmb)	Depth to Cavern Floor	Cavern Height, H	Cavern Diameter, D	Ф/н	Distance to Mearest Cavern, P	q/a	Simultaneous	Bingle or Multi- Well Leaching?	Type of Salt Deposit	Comments
United States Strategic Petroleum Reserve	34ª		5200	2000			_		Yeı	3 well	Doma.1	5 cycles of crude oil storage are anticipated
Initially		10			230	8.7	520 ^b	2.3 ^b				in design phase.
After 5 cycles		20			270	7.4	70 ^c -565 480 ^b	1. 5- 2. 1 1.8 ^b				
LOOP	14	5	2500	1000	190	5.3	380	2. 0	No	Single	Doma.1	Proposed facility for Gulf Coast dome for offloading supertankers. No fresh water cycling is proposed after con- struction.
West Germany (Etzel)	33	3	5 %	2000- 2132	102-164	12.2- 20.9	750 56-718	4-7	Yes	Single	Doma.1	KBB designed underground cavern complex.
French		. 4		4	a							Caverns appear from
Phase 1	18	.67 ^d	2630	1312 ^d	97 ^d	13.5 d		> 3 ^e	No.	Single	nticlina	sketches to be very irregular in shape
Phase 2	16	.14 ^d		1312 ^d	1111 ^d	ι1.8 ^d						(i.e., some have maximum/minimum diameter
Cavern A4				.1476	92 ^d 200 max	ւ6.						ratio > 5) French plan to use some caverns for yearly Cycling of prod -
Largest Cavern		3		1212	130	:0.1						ucts during peak demand times after fresh water cycling has leached caverns to maximum desirable size.

All dimensions are in feet.

a. Proposed expansion phase design has 12 caverns at Bryan Mound, 6 at Bayou Choctaw and 16 at West Hackberry. b. Data from site leach analysis reports.

c. Distance of 370' to nearest cavern is computed at the Bayou Choctaw site using the maximum size of the proposed new cavern 103 as related to the current size of existing cavern 20.

d. Average properties.
c. Estimated from site drawings.

cavities at a maximum depth of 2500' should have a P/D ratio of 2.8 for best results, separation less than the recommended value would increase volume loss dramatically beyond the 1-2.5% volume loss noted for P/D = 3.0. If the depth of the caverns were increased to that of the SPR caverns, significantly larger amounts of closure would be anticipated. In these "paper" studies [E-21, E-38, E-831 no correlation with any field data was presented and no reference was made to the use of site specific material properties. In a published study of rheological properties of rock salt from deposits in Northwest Germany and the related stability problems of storage caverns, Albrecht and Langer [E-84] state that if the geological conditions are ideal, a P/D ratio of 2.8 would be acceptable. The importance of the temperature dependent nature of the salt is described since a tenfold increase in the plasticity parameters is noted in going from room temperature to 100°C while the elastic modulus and the yield stress drop by a factor of 3-4. This observation of published data leads in Ref. E-84 to the statement that "it is essential. to test the (salt) samples at elevated temperatures".

Another way of viewing the question of the acceptability of the P/D ratio in a cavern complex is to consider the extraction ratio that accompanies various P/D ratios (Figure E-23). The extraction ratio for a cavern complex is the ratio of the planform area removed by cavity construction to the total area of the salt which surrounds the caverns. It is well recognized that storage complexes differ in many ways from mines and that the spacing of caverns is not generally based upon direct correlation with conventional mining practices. However, a comparison of the SPR design for new caverns with data from underground mines is offered to provide insight into important similarities and differences. For a hexagonal array of caverns the extraction ratio is given by the expression

$$ER = \underbrace{0.95}_{1 + P/D} \tag{E-6}$$

Similarly, the extraction ratio in a rectangular array is

$$ER = \frac{0.88}{1 \text{ t P/D}}$$
 (F-7)

Figure E-23 (developed using these equations) shows that there is little difference between the extraction ratios, calculated for the two types of cavern arrays. Furthermore, it is noted that the new SPR caverns (even after 5 cycles) will not exceed a 15% extraction ratio. A graph presented in Ref. E-85 depicts extraction ratio versus depth for 12 North American salt (or potash) mines which have stable pillars. This data would indicate that at 4500', it could be possible for an extraction ratio of greater than 20% to produce stable, freestanding pillars.

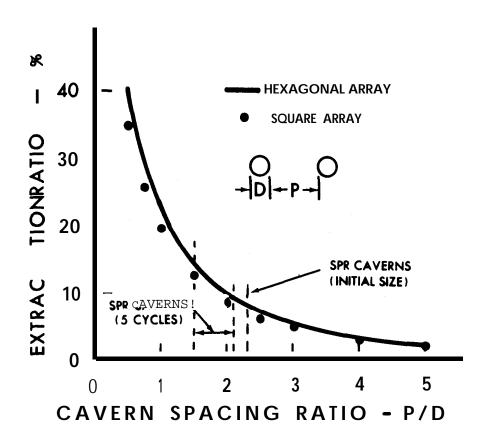


FIGURE C-23. Extraction Pat 10 Vsr lation With Cavern Spacing

Since the SPR cavern walls will be supported by the pressure of the brine head (occasionally just an oil head) it is difficult to envision (by only considering the extraction ratio) that a major instability of the caverns could result.

Further credence regarding the acceptability of the spacing proposed for the new caverns can be garnered from considering the existing caverns in the ESR program. Only one ESR cavern (West Hackberry #11) has a P/D ratio for the nearest adjacent cavern of greater than 2.0. While it is recognized that the ESR caverns cannot in general be interpreted as forming a complex over a large portion of their domes, it is nevertheless noted that many of the ESR caverns have existed for more than 10 years and have been evaluated as being stable under current conditions.

Hence, conflicting evidence is noted regarding the acceptability of the SPR spacing of new caverns. On the one hand, a simple attempt to correlate cavern spacing with mining experience (in terms of extraction ratio), SPR sponsored calculations, and the locations of existing caverns relative to each other would indicate that the new caverns should be stable. Alternatively, it must be recognized that both the German and French crude oil storage facilities utilize considerably larger cavern spacings than that planned for the SPR. Likewise, the spacing of the LOOP project exceeds that of the fully developed SPR complexes even though the maximum depth of the LOOP caverns is only 1/2 that of the SPR caverns. Additional efforts should be made immediately to assess the adequacy of the spacing in the new cavern development programs.

General Comparison with Other Storage Projects

In addition to the previously described specific comparisons made between the SPR program and other storage projects, there are other obvious contrasts which are of a more general or philosophical nature. It is noted that the radioactive waste disposal studies both at LSU [E-44, E-451 and in the WIPP project [E-36] as well as the Ontario Hydro studies are much more site specific than is the cavern design for the SPR program. Furthermore, the CAES program, the radioactive waste disposal studies, and the Canadian storage project each seek an integrated program in which concentrated efforts are devoted to developing laboratory and bench scale test programs which are closely coupled with numerical simulation efforts. These tests and numerical studies are then closely coordinated with the data obtained through active monitoring of field events.

The site-specific emphasis in the ongoing waste disposal studies and in the Canadian storage project is noted in almost all of the previously cited references. While a series of generic waste isolation studies [E-87] have been completed, current efforts in salt are being concentrated on site specific studies with some continuing emphasis upon studies of the potential usability of other materials such as granite, tuff and shale. The SPR design for new cavities as well as the geomechanical

analyses of the existing cavities have been made using generic (not site specific) properties for salt. The need for assessing the dome or site specific nature of the salt behavior is well established by the ongoing bore hole deformation studies by Thorns [E-88]. The deformation rates in similar holes drilled in the Vacherie and Rayburn domes differ by almost an order of magnitude. In addition, visual observation of the cores from Bryan Mound, Bayou Choctaw, and West Hackberry reveal substantial disparities in grain sizes. Case histories (such as those in Ref. E-89-E-91) clearly document the variability of salt properties from one location to another.

A coordinated effort comparing the design predictions with laboratory and field studies is evidenced in the CAES program, the Canadian study, and the waste isolation projects. This close relationship between the different design approaches and the field operations appears lacking in the SPR program. For example, no correlation has been made to date between the bench scale tests and the numerical simulations nor have numerical simulations been reported by SPR contractors in which the models are directly validated using field data.

Conclusions and Recommendations

The major technical areas requiring further investigation to assure cavern stability are described in this section and general programmatic recommendations as well as specific recommendations are offered. The basic conclusion offered in this evaluation is that final design of the new caverns and further evaluation of the existing caverns should parallel an expanded well-coordinated geomechanical investigation that addresses site-specific questions.

Technical Areas Requiring Additional Evaluation

Four major technical areas which require additional evaluation and investigation have been identified in this evaluation of the SPR program and are delineated below.

Cavern Spacing - The impact of the planned spacing of the caverns for the expansion phase should be studied in order that operations can be planned accordingly. The basis for the identification of cavern spacing as a potential technical problem are thoroughly documented in the preceding section. Comparisons with other storage projects and numerical simulations favor a larger spacing than currently planned while extraction ratio considerations, an SPR numerical study, and the spacing of the existing caverns tend to support the spacing selected. Additional investigation of the currently selected spacing is needed because of the programmatic, financial, and environmental impacts of cavity failure. It is likewise recognized that a decision to increase the cavern spacing would translate to either a substantial increase in construction costs if more land and caverns were required, a decrease

in storage capabilities for each expansion site, or to designs which must utilize cavern heights in excess of 2000 ft.

Depressurization Effects in Existing Caverns — The decrease in pressure applied to the walls of the storage caverns during either intentional or accidental depressurization of the oil column can potentially result in excessive creep closure, structural instability potentially resulting in roof failure, or damage to the emplaced drill strings. This sweeping statement should not be interpreted as a "prophet of doom" generalization of potential, but highly unlikely, failure but rather as a plea for a carefully planned and orchestrated program of investigation to assess the effects of this highly undesirable loading condition. This view is supported by the opinion of the previously described review panel [E-79] and by the description of Rohr [E-92] who reported the occurrence of a significant roof fall in a German cavity during a 2000 psi pressure drop. In particular, these effects should be carefully evaluated in West Hackberry cavern #6 because of its extremely wide, flat roof, in Bryan Mound cavern #5 because of the potential insoluble stringer, and in Bryan Mound cavern #2 because the casing seat is located at the top of this cavern.

<u>Cavern Proximity to Dome Boundaries</u> - Limitations placed on the allowable design distance between the edge of an ESR or SPR cavity and the flank of the dome should be carefully reviewed especially in relation to how accurately the edge of the dome is defined. Increased lateral stresses and decreased material homogeneity are often noted as the edges of salt domes are approached. Establishing communication between a cavity and the edge of a dome is as serious a problem as that associated with roof problems causing communications with the caprock. As previously noted, some of the existing caverns are much less than 200' from the projected dome boundary. Cavity communication with the strata surrounding the edge of the dome would obviously be more likely to occur than would complete cavity collapse. This communication could either be established during the opening of the cavern by dissolutioning into geologically anomalous zones (i.e., faults or zones of inhomogeneous salt), or during the operation phase by continual flow (creep) of the cavern walls. In selected cases, additional drilling to more accurately define the dome boundaries may be prudent.

Mechanical Testing of Salt Cores - A minimal number of quasistatic tests have been performed on cores obtained from the SPR drilling program at the-storage cavern sites. Creep tests at Sandia on SPR salt cores were conducted as part of this evaluation. The cavern design has used little data of a site specific nature in evaluating either the existing or the proposed new cavities. As the designs proceed toward construction phases and as an aid in site specific evaluation of existing cavities, more emphasis should certainly be devoted to establishing a data base of material properties commensurate with the needs of the SPR program. A

comprehensive program in this area should include creep tests, triaxial compression and extension tests, tensile strength tests and other appropriate tests designed to lead to an improved capability to more accurately characterize and predict more accurately the failure of salt. Tests would hopefully be concentrated on the evaluation of properties of salt from a single site and then, for additional sites, test matrices would be designed to index the salt properties relative to the well characterized site.

General Programmatic Recommendations

The following general recommendations are offered to enhance the credibility of the SPR design efforts. The data supporting the need for these recommendations is, in most instances, contained in previous sections of this appendix.

A. A coordinated program (including program definition documents) devoted to coupling the laboratory and bench scale studies, the numerical modeling efforts, and the results of judiciously selected field tests is necessary to increase confidence in the overall design approach.

Participants in this program must be allowed to pursue this goal and should not be relegated to total participation in "brush fire" analyses.

- B. Future geomechanics design studies for the new cavities should reflect much more site specific information.
- C. <u>Increase the level of effort expended in the geo-mechanical investigation of the existing caverns, including selected caverns which failed to meet certification requirements (see Tables E-5-E-8).</u>
- D. Identify instrumentation needs and, where feasible, develop techniques for enhanced cavern monitoring and for the improvement of design approaches, particularly the predictive capabilities of the numerical simulation studies.

Specific Recommendations

Numerous site and cavern specific recommendations are presented in Tables E-5-E-8. The documentation supporting these recommendations have been explicitly detailed in previous sections. These recommendations and the accompanying documentation are not repeated here. Additional recommendations regarding specific aspects of the cavern stability assessment and design efforts are presented below.

1. Perform extensive mechanical testing of the cores obtained from each dome including creep tests for use in assessing the long term stability of the existing and proposed caverns.

The information gathered from these tests should aid in establishing the potential variability in the response of the salt both laterally and vertically within a dome as well as from dome to dome. While it is assumed that quasi-static compression and tension testing will be done, creep tests (including triaxial extension tests) should be performed to establish anticipated creep properties for numerical simulations and to establish limits on the motion which can be sustained prior to failure or rupture of the salt. The failure information is crucial since this data can eventually impact cavern spacing.

2. Develop core and cuttings evaluation program for the bore hole drilling programs at each expansion site which obtain cores at selected depths from each hole.

This core evaluation program must be carefully designed to give sufficient overlapping of depths to allow an assessment of the lateral variation in properties while maintaining adequate sampling of the vertical column.

Current programs will provide no cores in the roof area; these plans should be modified if cuttings reveal even a hint of geologic anomalies in this region. Cuttings and cores should be inspected very soon after they are obtained so that appropriate modifications to existing plans (such as modifying new cavern locations) could logically be made.

3. Establish a core storage facility for the SPR drilling program to permanently store the material, catalogue the core, maintain accurate records of the core history, establish and implement procedures for supplying core samples to interested parties.

Because of the relatively transient nature of the involvement of the contractors of the SPR program, it is recommended that efforts be made to obtain the cooperation of either the USGS or of Louisiana State University personnel. This would place the maintenance of these cores in the hands of an independent, yet responsive, organization. LSU personnel have had a long term, continuous involvement in studying the behavior of Louisiana salt domes and would potentially have an interest in developing a facility such as this.

4. Develop program for monitoring bore hole deformation rates in selected bore holes and at various depths and perform extensive logging of these holes.

The cavern well drilling program for the expansion of each site should provide the opportunity for correlating field response (bore hole deformations) with the laboratory testing of cores removed from these holes.

Similarly these tests offer the chance for comparison and correlation with numerical studies. Of greatest importance, however, is the data which can be obtained to assess the inter- and intra-domal variations. Some holes which are required for leaching soon after completion may not be available for this calipering, but several holes at each site should, as a result of scheduling, be available for several months after drilling is completed. The opportunity to utilize bore hole deformation monitoring equipment should not be passed over since accurate measurements of the salt motion after drilling the hole can be made whereas measurements of the edge of a cavity can be assured at best only to within 5% of the radius. This monitoring has the potential for defining anomalous zones which, if first noted during continuous leach/fill operations, could have a severe economic impact.

- 5. The numerical simfilation efforts which support the cavern design should be correlated with results of field and laboratory tests.
- 6. Define and implement certification techniques for use in new cavities constructed using the simultaneous leach/fill concept and assess the certification techniques in current use.

The continuous leach/fill operation does not permit certification testing of the new cavern prior to filling. However, the potential economic impact of a cavern failure is obviously quite significant. A careful investigation of the information potentially gained from periodic overpressurization of a developing cavern during the leach/fill phase should be weighed against the potential for unnecessarily creating damage. Recommendations regarding continual certification testing of partially filled caverns should then be made.

Because the casing seat is so far removed from the roof of even the "ill-shaped" cavities in the SPR program (except Bryan Mound Cavern #2), it is unlikely that even large creep deformations in the cavity roof area during depressurization would result in significant motion of the casing seat. However, depressurization (either partial or complete) could conceivably result in damage to the grout surrounding the seat. It would therefore appear that the over-pressurization to maximum casing seat operating pressure limit may not represent the "worst case" loading anticipated by the seat. The potential information garnered from testing casing seats during a pressure drop (possibly followed by over-pressuring) should be evaluated.

7. Establish detailed field test program and plans for using the data for assessing cavern depressurization effects, for continual monitoring of high risk cavities and for

periodic monitoring of the storage cavity complex at each dome.

Microseismic and acoustic emission devices offer potential aid for monitoring the effects on roof integrity of depressurization. These techniques are, however, still considered to be in a state of advanced development rather than as an "everyday working tool", Pressurized bore holes offer a rather simple means of continuous monitoring to assess if major failure is occurring. Careful monitoring of wellhead pressures and flow rates must be maintained. A well coordinated plan for monitoring the storage cavity complexes over a several year period (up to 15 years) should be developed now and subsequently modified as site specific needs arise.

Appendix F

Geomechanical Assessment/Weeks Island Mine

The existing Morton Salt mine at Weeks Island is being converted to a crude-oil storage. The design includes a provision for Morton Salt to develop a new mine beneath the converted mine. A program has been carried out to certify the existing mine for crude-oil storage and to determine a safe vertical separation (web thickness) between the storage horizon and the projected horizon for the new mine site [F-1,F-2]. References F-1, F-2, and F-3 report on:

- Visual inspection of the mine for deterioration, slabbing, leaks, etc.
- 2. Coring to obtain material properties samples.
- 3. Pressure 'tests of fuel-oil in core holes to determine leak rates and/or permeability.
- 4. Laboratory tests on core samples to determine deformation and failure properties of the salt.
- 5. Numerical (finite-element methods) elastic and elastic-plastic stress analyses of a single mine level and of the interaction between the existing mine and the proposed mine.

An analysis of the interaction problem provided the basis for specification of required web thickness between the existing and proposed mines. References F-1, F-2, and F-3 state that the possibility and/or influence of outbursts had not been included in that analysis. The reports strongly recommended further investigation of this topic.

While it is generally agreed that existing outbursts at the Weeks Island mine do not substantially reduce its structural integrity; the pertinent questions to be addressed are:

- What are the size, number, and location of the outbursts likely to be encountered during future mining?
- 2. What influence will they have on the integrity of the oil reservoir/salt mine combination?

The number and size of outbursts vary significantly from one mine to another. The largest known outburst in a Louisiana salt dome had a depth of approximately 280 feet. Three substantial outbursts have been observed at the Weeks Island mine; they are approximately cylindrical in shape with a 30 foot diameter and a 30 foot depth.

The analysis described in this appendix was directed toward ascertaining the structural integrity of the mine when employed for crude-oil storage. Finite-element stress analyses were performed for a single-level mine model and for two-level mine configurations with various vertical separations. These analyses were in support of the earlier work by Acres American for certification of the mine [F-1, F-2, F-31. The influence of outbursting on structural integrity was addressed using two approaches. Stress analysis was performed for a two-level mine with a simulated outburst in the roof of the lower mine. Additional analysis was employed to predict the regions of reduced pressure associated with new mining where outbursting was possible.

Modeling of Deformation and Failure for Room and Pillar Salt Mines - The short time response of salt was approximated as elastic-plastic deformation. The associated short time failure mechanism of concern is fracture. Fracture toughness testing of salt at Sandia is planned as part of Sandia Laboratories' WIPP* Program. Data gathered during the WIPP program will be available in the near future. A more limited but site specific set of data has been developed for the Weeks Island mine by Acres American [F-3] . A Mohr's envelope of failure conditions is reported there indicating practically zero tensile strength. Thus at the present time, a given design is believed to be safe. from fracture provided all principal stress components are sufficiently compressive. The longer time response (days-years) for salt is creep. Creep in mines causes stress redistribution and eventual slabbing. Creep theories applied to salt are of the von Mises stress type (alternatively termed "effective stress") relating creep strain rates directly to the magnitude of this stress measure. Thus von Mises stress contour plots were developed to assess future straining behavior.

The criterion employed in the certification studies [F-1,F-2, F-31 for choosing a minimum web thickness was that there should be no stress interaction between the mines, i.e., that the web should contain a region of undisturbed in-situ stress. It is believed that this criterion, is generally conservative. Instead it is proposed that effective stress and related creep strains be considered as the basis of design against "long" time, creep induced failure. Also it is proposed that the algebraically largest principal stress be used as a parameter for design against short time fracture. Elastic-plastic and creep analyses were performed to determine the distributions of these quantities.

^{*}WIPP: Waste Isolation Pilot Plant currently being studied as a repository for nuclear waste in bedded salt.

<u>Stress Analyses</u> - The finite element analyses reported herein were performed using the ADINA code [F-41. Three material models were employed as appropriate:

- 1. Elastic response: $E = 2 \times 106 \text{ psi}$, v = .42
- 2. Elastic-perfectly plastic, Drucker-Prager Yield Surface

$$\psi$$
 = 56°, C = 330 psi

3. Secondary creep model $\varepsilon = (2.58 \times 10^{-12})$ (a ³ • ') (t)

The values used for elastic material properties and for the Drucker-Prager yield surface parameters were those presented in Reference F-2, which are believed to characterize Weeks Island salt. The creep parameters on the other hand, are generic values for salt employed in other applications at Sandia Laboratories[F-51.

Stress analyses are presented here for single and multiple level mines. Simulations of outbursts were also performed and are presented.

Single Layer Mine Model - Baseline calculations involving the geometries, material properties, and loading conditions analyzed in Reference F-I were performed first to demonstrate consistency with this earlier work. A single layer room and pillar mine was used to simulate a typical pillar with adjacent floor and roof regions by the axi-symmetric geometry whose grid pattern is displayed in Figure F-I.* The model supports overburden pressure on its upper horizontal surface. Its outer boundary is prevented from lateral motion. The pillar edges are traction-free while no vertical motion is allowed in the lower surface.

^{*}Eight node quadratic elements were used in all of the calculations reported here. Each eight noded element is represented by four linear elements on the plots that are shown.

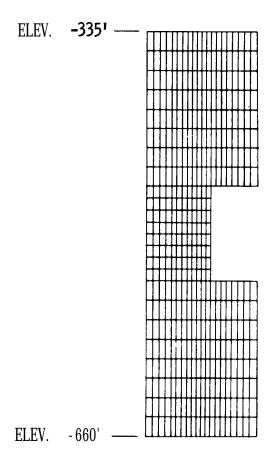


Figure F-1. The Grid Pattern for the Finite Element Analysis of the Single Layer Mine Model.

Principal stress contours shown in Figure F-2 indicate close agreement with Reference F-1. Figure F-2a displays maximum in-plane stress contours; Figure F-2b shows minimum in-plane stress contours; and Figure F-2c shows the circumferential or hoop stress components.

The same grid pattern was used in conjunction with the secondary creep model to study the room closure characteristics. The calculations employed the small strain formulation of the ADINA [F-4] code. Figures F-3a and F-3b are the deformed grid patterns plotted at .55 years* and 5.05 years. Figures F-4a and F-4b show the corresponding von Mises stress fields and indicate little change in the variable with time. The von Mises stress drives the creep strain. As little change in von Mises stress contours with time have been predicted, straining can be expected to continue at approximately the same rate.

The inclusion of large deformation influences in the creep analysis may lead to greater changes in the stress field with time. A comparison of a linear small strain prediction with results employing the large rotation option are presented later for a more severe stress state. These results suggest that corrections for large rotations in this problem would be small.

Two Level Mine Models - The interaction problem of the crude-oil reservoir with the proposed mine was considered in some detail. One of the geometries considered by Reference F-2 was repeated here as a baseline calculation. The grid pattern for this plane strain model with a 90 meter web thickness is shown in Figure F-5. The boundary loads are: (1) overbur pressure on the upper surface and (2) hydrostatic pressure (1) overburden including appropriate variations with depth along the right lateral edge. The left edge was treated as a symmetry plane and the bottom was supported by rollers. Some effort was expended to enforce appropriate displacement of the loaded edges, i.e., beams with small cross-sectional area and large moment of inertia were added to the right vertical boundary to prevent local distortion of this edge. Bending of the upper region was prevented by constraining the horizontal motion of the nodes on the top surface. Material behavior was modeled as elastic-perfectly plastic with the Drucker-Prager yield surface described earlier. Figure F-6 is a plot of the von Mises stress contours resulting from this calculation. These results are in close agreement with Reference [F-2].

^{*} The secondary creep model is expected to underestimate the short time creep deformation.

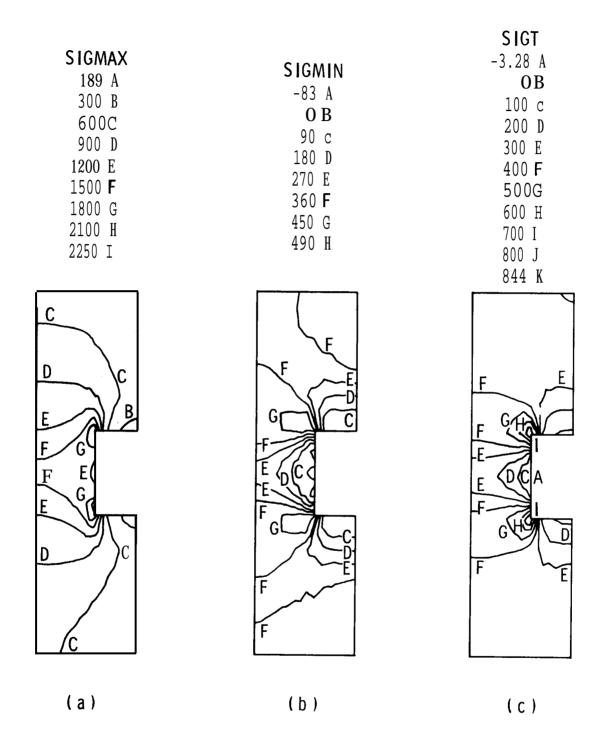


Figure F-2. Contour Plots of Principal Stresses (psi)

5. 05 YEARS 5. 05 YEARS (a) (b)

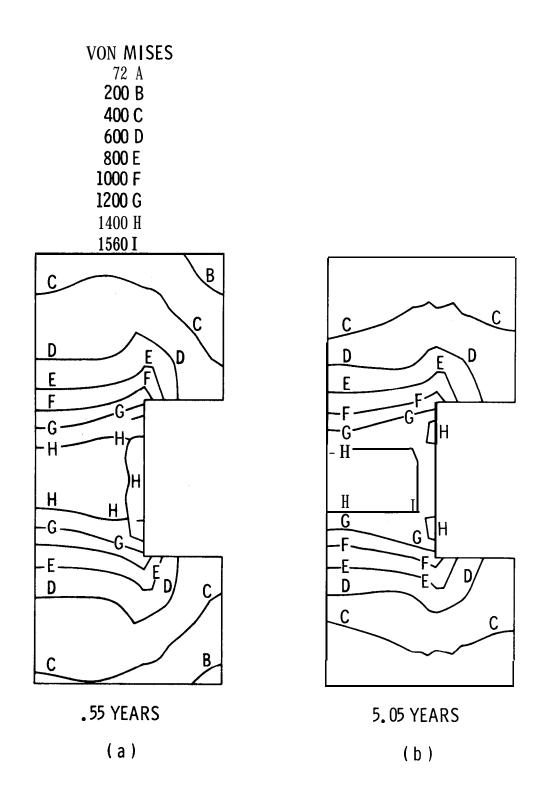


Figure F-4. Contour Plots of von Mises Stress (psi)

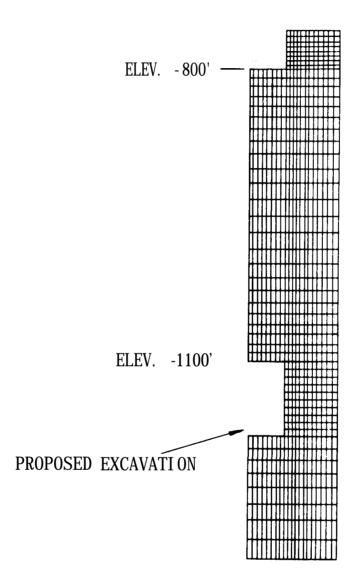


Figure F-5. Geometry and Grid Pattern for Two Level Mine Interaction Calculations

VON MISES

OA 200 B 400C 600 D 800 E 1000 F 1200 G 1400 H 1600 I 1730 J

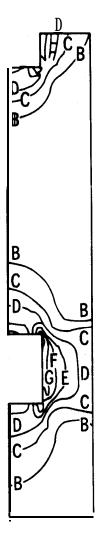


Figure F-6. Contour Plot of von Mises Stress (psi)

Creep calculations were performed for the same geometry to determine the long time stability of the lower cavern. Gravity loading, believed to have been omitted in the Reference F-2 work, was included here. Figures F-7a and F-7b show the grid pattern deformations in the region of the lower room. These predicted deformations are considerably larger than those in the upper rooms. Corresponding von Mises stresses are plotted in Figures F-8a and F-8b.

The finite element analysis of this case was repeated using the total Lagrangian option in ADINA which includes the effect of large rotations. The resulting von Mises stress contours at 5.05 years are shown in Figure F-9. It should be noted that the inclusion of large rotations has a minimal influence on the resulting stress field. This result was employed to justify use of the standard small strain formulation elsewhere in this work.

The creep calculations were repeated for a 200 foot increase in web thickness. Corresponding plots of deformation and von Mises stress are presented in Figures F-10 - F-11. The deformation and effective stress increased over the previously modeled case.

Outburst Simulation Model - The effect of an outburst on structural integrity was modeled by an axi-symmetric room and pillar geometry including a cylindrical cavity. The cavity was located in the roof of the lower mine with a radius of 20 feet and height of 150 feet. Shown in Figure F-12 are the deformed grid patterns without and with the outbursts respectively. Both elastic and elastic-plastic calculations were performed to determine the short time response of the outburst model. The loading and boundary conditions employed were:

- 1. overburden pressure on top
- 2. hydrostatic pressure on lateral edge
- 3. gravity loading
- 4. no vertical displacement on lower edge

Beams were employed to enforce straightness to the vertical boundary. Results comparing the effects of the outburst for both the von Mises and the algebraic largest principal stresses are shown in Figures F-13 and F-14. The von Mises stress contours give information **about** expected creep behavior. More important for this situation is the possibility of short time failure. The maximum principal stress contours are the basis for assessing such failure with regions of zero or tensile principal stress considered to be unstable.

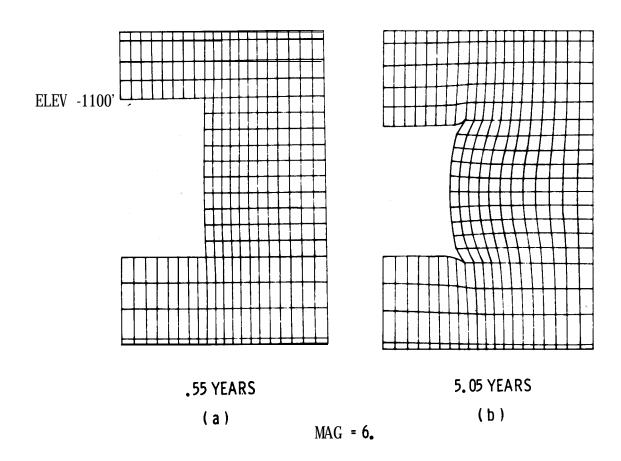


Figure F-7. Creep Deformation of Region Surrounding Lower Mine

VON MISES 99. 2 A 200 B 400c 600D 800E 1000 F 1200 G 1400 H 1600 I 1630 J .55 YEARS 5.05 YEARS (a) (b)

Figure F-8. Contour Plot of von Mises Stress (psi)

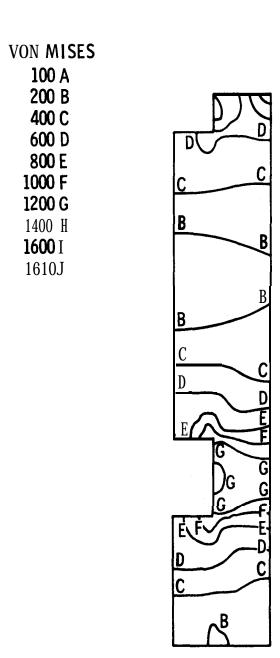


Figure F-9. von Mises Stress Contours \boldsymbol{from} Total Lagrangian Calculation

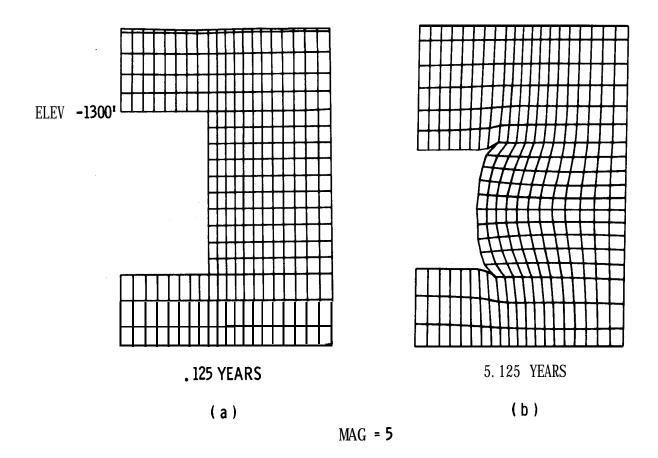


Figure F-10. Creep Deformation of Region Surrounding Deep Lower Mine

VON MISES 97.7 A 300 B 600 C 900 D 1200 E 1500 **F** 1800 G 2100 H 2150 I . 125 YEARS 5. 125 YEARS (a) (b)

Figure F-11. von **Mises** Stress Contours (psi)

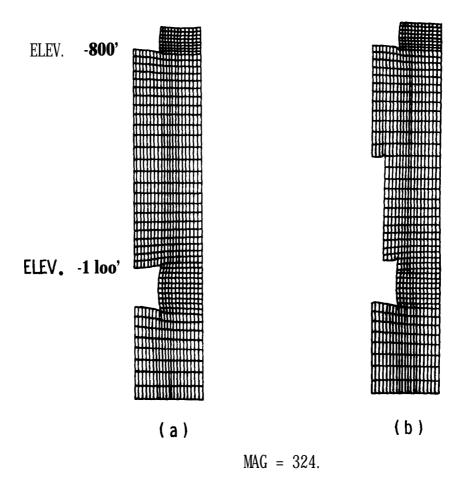


Figure F-12. Deformation of Existing and Proposed Mines (a) without and (b) with a simulated outburst

VONMI SES 0 A 200 B 4OOc 600 D 800 E 1000 F 1200 G 1400 H 1590 I

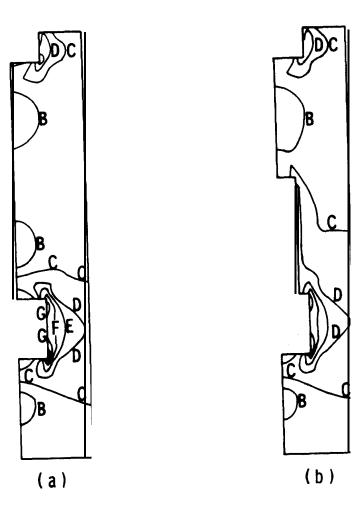


Figure F-13. von Mises Stress Contours Showing Influence of a Simulated Outburst

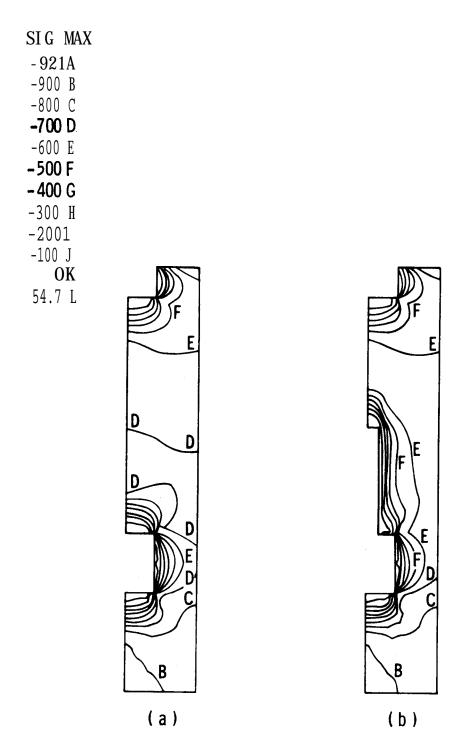


Figure F-14. Maximum Principal Stress Contours Showing Influence of a Simulated Outburst

Results of Numerical Stress Analysis as Basis for Evaluating Design - The interaction stress analyses which do not include simulated outbursts indicate that the largest values of both effective stress and largest principal stress occur in the immediate vicinity of the lower pillar. Increasing web thickness and, as a consequence, the depth of the lower mine actually produce an increase in these quantities over the range considered (300 - 500 feet web thickness). This suggests that the stress fields are influenced more by the overburden loading then by the above mine and oil pressures. Increased web thickness will thus reduce the structural stability of the lower mine (for a given extraction ratio).

The influence of outbursts on the stress field was simulated by a cylindrical cavity in an **axi-symmetric** approximation to the structure. The important results of this analysis are:

- 1. The "outburst" simulated here does not substantially influence the stress state in the immediate vicinity of the pillar.
- principal stress are smaller around the simulated outburst than in the vicinity of the pillar. Further there is little or no interference of stress contours between the two mine levels with the simulated outburst. Thus, even the "damaged" mine satisfies the design criterion proposed by Acres American [F-1, F-2, F-31 for sufficient separation between the mine levels. Consequently, the structural integrity of the mine is not significantly altered by an outburst of the size simulated here.

The real concern with regard to outbursts is that they could lead to sudden interconnection between the reservoir and the active mine. This could only occur by:

- 1. An outburst which subsequently results in fracture of the remaining ligament of web, or
- 2. An outburst which connects both levels.

Results indicate it is unlikely that an **outburst** could lead to fracture of the remaining ligament. The outburst simulated did not produce a more severe stress state than that already existing in the vicinity of the lower pillar. The second point is addressed in the following sections leading to the prediction of regions in which **outbursts** are possible.

Stress Analysis Prediction of Regions Where Outbursts in Salt Mines Can Occur - Dames and Moore [F-6] studied the potential problem of outbursts at Weeks Island Mine for Morton Salt. Their report included an extensive reference list on the topic of outbursts. A more accessible review paper on outbursts is given by Thorns and Martinez. [F-7]

Outbursts in salt formations result from entrapped gas at the crystalline grain boundaries. The gas diffused to the grain boundaries from high **pressure** pockets formed during geological motion of the salt, e.g., the formation of salt domes. It is in pressure equilibrium with the local in-situ pressure. During mining, this pressure is relieved at cavern walls as a result of the formation of the mine. Thus, the gas in the vicinity of the opening is no longer in pressure equilibrium. Either an outburst will occur during the mining process, or the entrapped gas will diffuse toward regions of reduced pressure (the mine surfaces), and therefore diminish the possibility of outbursts at later times.

Outbursts are expected to occur when the effective pore pressure minus the stress induced pressure reaches a critical value for that particular salt. The act of mining causes a sudden reduction of the stress related pressure in the material adjacent to the portion just removed and thus can produce outbursts. Numerical stress analysis was employed to predict this pressure difference and thus map the regions that, if they contain gas, are likely to have outbursts. Two mine configurations were treated:

- 1. Extension of an existing mined room.
- 2. Extension of the lower mine room in a two-level mine.

The second problem has relevance to the interaction of existing and new mining. Results from it will be used to discuss the possibility of an outburst resulting in communication between the two mines.

Model of Gas Diffusion — A first order model of the process of gas diffusion in salt follows. Darcy's law relates volume flow rate per unit area $\vec{\textbf{d}}$ to pressure gradient $\vec{\textbf{vp}}$ in terms of permeability k, and viscosity μ :

$$\vec{\mathbf{u}} = -\frac{\mathbf{k}}{\mu} \vec{\nabla} \mathbf{p}$$

Continuity of mass yields:

$$n \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

where ρ is the mass density and n is porosity. If, in addition, an ideal gas is assumed such that density (ρ) is proportional to pressure (p) , then:

$$\frac{\mu n}{p} \quad \mathbf{a}_{t} = \stackrel{\rightarrow}{\nabla} \quad \bullet \quad (k\nabla (p^{2}))$$

Assuming constant permeability (k) is given, then:

$$\nabla^{2}(p^{2}) = \frac{n\mu}{kp} \frac{\partial(p^{2})}{\partial t}$$
 (1)

An analogy with the heat conduction equation enables **use** of heat transfer solutions for prediction of pressure diffusion. The analogous "heat conduction coefficient" $K = kp/n\mu$ gives information about the rate of diffusion. Typical values of the parameters for the Weeks Island mine are [F-7]:

n = 6%, k = 630 millidarcys at 100 psi overburden pressure, $\mu \approx 10^{-2} \text{ centipoise}$

At a pressure of 500 psi, this gives the analogous K $\approx 50\,$ cm²/sec.

A special case of Equation (1) where an analytic solution is available is discussed to indicate the rate of diffusion. The one-dimensional semi-infinite heat conduction problem with uniform initial conditions (T_0) and imposed zero temperature at the end has the solution:

$$T = T_{o}erf\left(\frac{x}{2\sqrt{Kt}}\right)$$

Thus, the approximate solution for pressure given an in-situ pressure (Po) and zero pressure imposed at the free surface is:

$$p^2 = P_0^2 erf\left(\frac{x}{2\sqrt{Kt}}\right)$$

Note that the pressure squared is a function of only one non-dimensional variable:

$$\rho = \left(\frac{x}{2\sqrt{Kt}}\right)$$

The local pore pressure is approximately the in situ pressure at $\rho = 2$. Thus, the region of significant diffusion is where ρ is less than unity, i.e., $x < 2\sqrt{kt}$. A table of values follows:

t	2√Kt		
l hr.	25 ft.		
l day	125 ft.		
1 month	700 ft.		

The approximate results presented above were used only to attain an understanding of the time scale of the **diffusion**-relaxation process. In particular, note that the time for significant pore pressure diffusion is large compared to the time rate for ore removal by **blast** mining. This result is used to make the assumption that will enable a significantly simplified analysis, i.e., immediately after a blast mining operation the pore pressure is that which existed before the blasting; however, the macroscopic pressure associated with stress is well approximated by the static stress analysis of the new (after **blast**) mine geometry. Thus, the difference in macroscopic pressures between the before and after blast cases (Δp) will be available to drive outbursts and/or diffusion. For this reason, calculated pressure difference contours were plotted. Regions in which this pressure difference is above **some** critical value (experimentally determined for the salt) were said to be outburst prone. The use of "outburst prone" is

different from the standard usage: it implies that if gas then exists in this region, it will outburst. The normal use of outburst prone is in reference to regions containing gas.

The approach lead to an indication of the regions in which outbursts were possible because of geometry and mining techniques. Calculations show that it is most unlikely that an outburst could connect a new mine to an existing mine because the region surrounding the existing mine opening has a low pore gas pressure.

Stress Analysis - Finite element stress analyses wdre performed with the ADINA Code (F-41 for the grid pattern and shape shown in Figure F-15. The cut out region idealizes an existing room in a mine and the shaded region is the "to be mined out" region. The plane strain approximation was employed. This grid was subjected to an overburden pressure on the top horizontal edge of 500 psi and the same pressure was applied to the left vertical edge. The right edge was treated as a symmetry plane and prevented from horizontal motion, and vertical motion was prevented on the lower boundary. The "room edges" were traction free. The calculations used elastic material properties; refinements to include nonlinear effects were recommended for predicting more detailed responses.

It should be noted that the employed loading conditions model hydrostatic in-situ stress at the overburden level. This assumption is accurate in the interior of a salt dome away from shear zones or other indications of inhomogenity. However, gas is most often found in anamolous regions. The gas may have resulted from high pressure pockets formed during the up-lifting of the dome. Since it is difficult to estimate the in-situ stress in these analomous zones, more appropriate boundary conditions would not be specified at the time.

Figure F-16 is a contour plot of the mean stress after room enlargement minus the mean stress in the original configuration. Regions of positive mean stress difference signify that the local pressure is below the *pore pressure and* thus outbursting is possible. Such regions are found above and below the newly mined section. Experimental data are needed to determine the pressure difference required to drive an outburst. Thus these predictions are only qualitative but they do predict the increasing likelihood of outbursting with increasing pressure difference.

A first approximation to the interaction problem of a pre-existing mine above a new mine currently being expanded is

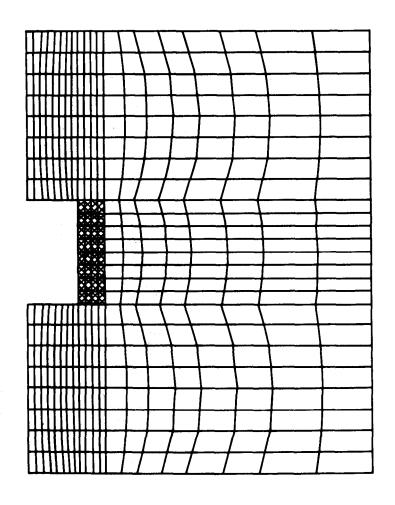


Figure F-15. Grid Pattern

```
EPSR
-974 A
-800 B
-600 C
-400 D
  -200 E
  0 F
200 G
     400 H
     600 I
762 J
                                                        Difference Contour
```

Figure F-16. Mean Stress

presented next. This idealization was accomplished **using the same** geometry, Figure F-15, but removing the overburden pressure from the top horizontal edge (thus simulating the floor of an above mine). Figure F-17 shows pressure difference contours for this case. **Note** that the region of positive pressure difference (outburst prone) above the new mining are reduced considerably in size. On the other hand, the "outburst prone" region forward of the new mining appears to be enlarged as a result of the interaction with the simulated above mine.

In order to determine the sensitivity of these results to the separation distance between the mines, the interaction problem calculation was repeated with a reduced web thickness, The pressure difference contours are displayed in Figure F-18. The pressure difference contours do not greatly change with decreasing separation in this range. It should **be** observed, however, that the region of positive pressure difference (outburst prone) in the web was reduced in size with the reduction in web thickness.

These preliminary results imply that it is unlikely that an outburst could connect new mining with an existing mine. This is illustrated in Figures F-17 and F-18 for two separation distances. The rationale (or interpretation of numerical results) which led to this conclusion is that the existing mine surface is at low initial pressure such that little additional pressure relief in the vicinity of the old mine can be created by the new mining. Similar predictions are expected for other mine shapes and conditions.

In **actual** practice at Weeks Island, mining at the lower level will be subsequent to crude-oil filling. The pressure induced by the oil will **cause** compression in the vicinity of the upper mine further reducing the likelihood of outbursting in that region.

Additional work is needed to better quantify **the results** presented here. In particular, laboratory efforts are required to measure the pressure difference level which causes outbursting in salt. When **such** information becomes available, more geometrically detailed idealizations should be employed to obtain more specific predictions concerning regions where outbursts may occur.

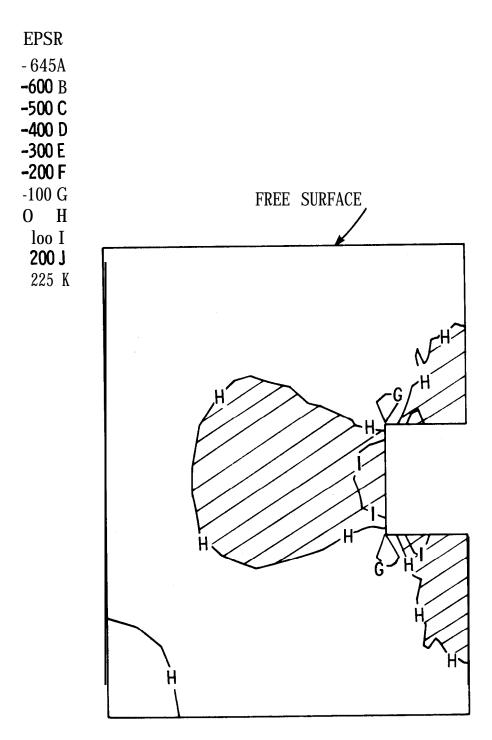
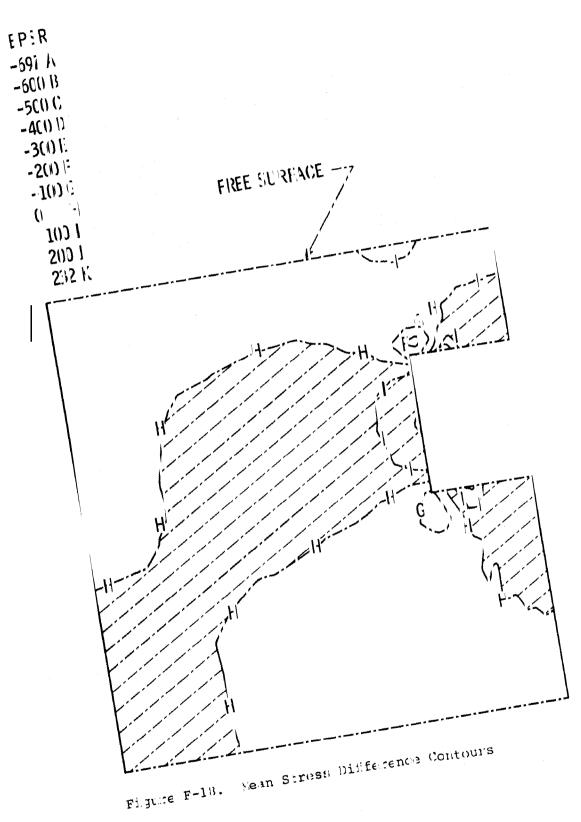


Figure F-17. Mean Stress Difference Contours



General Conclusions

- 1. Stress analysis performed here confirmed the results presented by Acres American [F-l, F-2, F-31.
- 2. Additional stress analysis of the two-level mine configuration indicated that the 300 foot vertical separation proposed by Acres American [F-l, F-2, F-31 is adequate to maintain web integrity.
- 3. Simulated outburst stress analyses demonstrate that the influence of an outburst is local and does not substantially reduce the integrity of the web.
- 4. Numerical prediction of regions in which outbursting is possible indicate that it is unlikely that an outburst in the new mining region will cause communication with the oil reservoir.

30F

Appendix G

Three-Well Leach/Fill Concept

Background

The three-well per cavern leach/fill plan for the expansion phase of the SPR, as outlined in the PB/KBB leach/fill study reports and the DOE Base Line Execution Plan for Expansion Sites [G-1,G-2,G-3,G-6] has been reviewed. The three-well leach/fill concept involves simultanous leaching and oil filling through three equally spaced wells to form three caverns initially which coalesce to form a single cavern as leaching progresses. The expansion plan also calls for simultaneous leach/fill of six to eight caverns at a site.

The original impetus for the three-well per cavern concept and the simultaneous leach/fill of several caverns was to achieve maximum oil storage in the shortest time with a 13-3/8 inch well size constraint.

The three-well leaching scheme was conceived in an attempt to meet original oil storage goals while staying within the 13-3/8 inch well size constraint. This well size was selected at the time to minimize equipment and rig availablility problems. The expansion plan and storage goals have subsequently been changed on several occasions while the three-well concept has been maintained [G-1-6]. Although the three-well concept offers earlier oil storage compared to a proven single well leaching approach, the concept involves a new, untried process involving greater cost and risk.

Oil Storage Schedules

The current expansion plan for Bryan Mound and West Hackberry consists of 120 MMB by 1985 and 160 MMB by March, 1986, respectively.

Studies by PB/KBB and by DUCI [G-4,G-5] compare the cost and oil storage rate for the three-well approach with those of a single 20 inch well for the current Bryan Mound expansion plan of 12 new caverns (120 MMB) and the West Hackberry plan of 16 new caverns (160 MMB). The PB/KBB study shows the following oil fill schedules for the two different approaches at these two sites based on the current expansion plan.

Cumulative Oil Fill (MMB)

	Single 2	20 Inch	Three 13-3	
Date	Well/Cavern		Well/Cavern	
	ВМ	WH	BM	WH
1980	0	0	0	0
1981	22	10	22	10
1982	35	30	36	34
1983	61	65	64	74
1984	88	10 2	92	115
1985	114	138	120	155
1986	120	160	120	160

The DUCI study concludes that although oil fill can begin approximately one year sooner under the three-well plan than under the large single well plan, the oil fill goals in the revised DOE expansion plan can be met under either concept at both sites.

costs

Significant cost saving for cavern development under the single large well plan compared to the three-well plan is estimated by PB/KBB. A corresponding savings is estimated by DUCI. These differences in cost are due largely to well construction costs (eighty-four 13-3/8-inch wells versus twenty-eight 20-inch wells). The net savings, in real dollars, that could be realized, is dependent on oil procurement policy and oil prices over the filling period, 1981 through 1985, and can only be determined from an economic analysis.

Risk

The degree of additional risk is unknown, is subject to debate, and is difficult to assess quantitatively, but there is some risk associated with just the unknowns of any untried concept involving relatively complex physical and chemical interactions and processes such as the planned three-well leach/fill concept. The apparent risk is associated principally with possible damage to the suspended casings and/or brine strings from a falling mass of salt during leaching: with the requirement that three wells, rather than one, be operable at all times for leaching (cavern formation) to progress in a controlled manner: and with the cavern growth and leaching time predicted from a numerical model that has not been proven in the planned mode of usage.

In the three-well leaching process, control of the formation of the three caverns into a single cavern in a way which will minimize the probability of a large mass of salt falling into and bending or breaking a suspended casing and/or brine string is dependent on the accuracy of the relative spacing of the three boreholes and on the homogeneity of the salt and symmetry of leach ing .

The prescribed tolerance on the spacing of the three wells, based on directional drilling techniques, is \pm 5 feet. With this tolerance on borehole spacing, a cantilevered web of salt could exist between a pair of the caverns as the remaining cavern coalesces from the top down. The length of the cantilevered web could be as great as 40 feet. A stress analysis of the web acting as a cantilevered beam with an evenly distributed load (the weight of the salt) indicates that the tensile stress in the salt at the base of the cantilever will exceed the allowable tensile strength (300 psi) when the height of the web is reduced to less than 20 feet. The weight of the cantilevered web of salt at that point is greater than 1 million pounds. This mass and size of falling salt could damage one of the brine strings. If the tolerance on well spacing exceeds \pm 5 feet, the risk of falling salt increases.

Similar or worse situtations can also exist if non-homogeneous salt is encountered in which uncontrolled leaching occurs in the connecting webs of salt between the caverns. After coalescence of the three caverns at the top, there remains a massive spire of salt up to 500 feet high in the center of the caverns which is no longer supported by the connecting web between the caverns. If uncontrolled leaching occurred at the base of this spire (as a result of an inclusion of highly soluble material), the spire of material would fall possibly damaging the brine string or casing.

The probability of damage to suspended casing or brine string from falling salt can be minimized by frequent sonar surveys to detect potential problems followed by adjustments in the raw water flow rate in one or more of the three wells. These operations add time to the leach/fill schedule.

If the logic behind the incorporation of more than one well per cavern to maintain a higher reliability during withdrawal is applied to the cavern/leaching process, then a single well should be used for leaching because it has a higher reliability than the simultaneous three-well leach concept. Being dependent on the simultaneous operation of multiple wells for leaching reduces the reliability of continuous operations below that for a single well. In the three-well concept, perhaps leaching could be continued in only one or two wells for a short time without drastically affecting the desired cavern geometry, but the time is unknown.

In the three-well process expansion phase, oil delivery to the sites is planned to be at a nearly constant rate. The validity of this plan is questionable because of the nature and complexity of oil fill in the three-well process. The three-well process requires intermittent injection of oil into each cavern during the early stages of leaching to control cavern formation. Intermittent injection of oil into each of six to eight caverns in various stages of completion in such a way that the overall demand for oil at a site is at a nearly constant rate will be difficult to achieve considering the complexity of this operation and the unknowns of the three-well process. The on-site storage capacity

may, at times, be exceeded. The flexibility of pumping oil between the ESR and the expansion caverns to meet the intermittent requirements and maintain a constant site demand rate will be limited because of the restriction on mixing crude types. Use of this procedure also presents the risk of inadvertent mixing of crude types. In the single well leaching process, once oil injection is begun, it may be continued at a constant rate until leaching is completed and the cavern is filled.

The purpose of the foregoing discussion is to emphasize that the planned three-well leach/fill expansion program is based on an untried process which involves **some** unknowns, an added degree of risk, and entails added costs. Delays in the leaching program caused **by** a single well failure, delayed leaching in one or two wells per cavern to maintain symmetry in the three caverns, down time to replace damaged casing or brine string, or downtime to conduct sonar surveys more frequently than planned to aid in control of leaching could combine to negate the advantages in earlier oil fill projected for the three-well concept. From an overall program view, the gains in the oil fill schedule appear **small** compared to the increased cost and risk associated with the three-well concept.

It is recognized that at this time (the cavern wells are being drilled at Bryan Mound) a change in plans would **cause** delays in the program. However, considering the changes in the expansion plan and storage goals since the three-well plan was adopted, it is recommended that the single well leaching concept be reexamined. In any event, it would **be** prudent to have a backup plan developed based on a single well leaching process which **can** be implemented in the event that significant problems develop with the implementation of the three-well plan.

Solution Mining Computer Model

The numerical model for simulation of the solution mining process developed by Intercomp, Inc. and KBB [G-9] was used in the design of the three-well cavern concept and in the cost-time comparison studies of a single well versus the three-well leach/fill process [G-4]. The original model used in the German solution mining cavern program required modification to adapt it to the three-well concept. No tests have been conducted to verify the adequacy of this modified numerical model to accurately predict cavern formation 'and leaching time for the three-well concept. A numerical model for single well leaching has also been developed at the University of Texas (Saberian and Podio) for the Solution Mining Research Institute (SMRI) [G-10,G-11]. There are basic differences in the assumptions and equations used in the derivation of these two solution mining models, First, it must be noted that both models are based on an assumption of homogeneous salt. A basic difference between the two models is that the Intercomp model makes use of Darcy's equation for flow in a porous media to calculate fluid flow velocity in the cavern while the SMRI model depends on an empirically-derived plume

model. In our opinion, a basic shortcoming of the Intercomp/Nolen model is the use of Darcy's equation. This inadequacy is evidenced by the fact that 15-20 computer runs with varying mass transfer coefficients were necessary to accurately simulate the formation of the caverns in full scale tests. The results of full scale tests on two caverns using the SMRI model demonstrated its accuracy and usefulness as a predictive tool for a single well leaching process.

It is questionable that either of these simulation models can be modified to accurately predict the simultaneous three-well-leach process because of the change in flow and boundary conditions as the caverns coalesce. To our knowledge, no direct comparison of the two models has been made by running identical problems and verifying the results with full scale or model testing to determine which of the computer programs is the most accurate and useful predictive tool.

It is our understanding, however, that the SMRI/Saberian model will now be used for implementation of the expansion phase. The SMRI/Saberian model will also require modification to adapt it to the three-well concept and is unproven in that mode. In summary, the design of the three-well concept and the decision to go with the three-well concept in the expansion phase was based partially on the results from a numerical computer model which is unproven in the three-well mode. Implementation of the three-well expansion plan will. be based on a significantly different numerical computer model which is also presently unproven in the three-well mode.

Fok the expansion phase of the program it is desirable to have a proven computer model which will serve as an accurate predictive tool. Since the Intercomp/KBB model is proprietary, it is recommended that an investigation be made as soon as possible to determine if the SMRI model can be modified to accurately simulate the simultaneous three-well process. If such modification appears feasible, it is recommended that the feasibility of verifying the code with a laboratory scale model be investigated. A full scale test verification can be conducted on the first three-well cavern to be leached at Bryan Mound.

Appendix H

Material Corrosion

An important technical consideration for the viability and reliability of the SPR program is the compatibility of system components with their environment (which in this case, is aqueous corrosion). An analysis of corrosion problems that either exist presently or might arise in the future, the potential severity, and recommendations to alleviate or to minimize cor ros ion was accomplished. The initial efforts included:

1) Extensive discussions with various personnel from SPR in New Or leans, Parsons-Gilbane Co., PB/KBB, and Dow Chemical Co. to determine from their experience what problems potentially exist, and 2) To use applicable data from the literature and to apply first principles of corrosion to assess the magnitude of the problems. The corrosion analysis was considered in terms of the following system components:

1) Interior pipeline corrosion by surface soil water,

3) Exterior downhole casing corrosion by acidic waters in the caprock, and 4) Galvanic corrosion of equipment. This analysis indicated that potential problems exist in areas 1 and 3.

Summary of Analysis

<u>Interior Pipeline Corrosion by Brine</u> - Steel corrodes in water according to the following reaction when oxygen is not present:

Anodic reaction: Fe =
$$Fe^{2+}$$
 t $2e^{-}$ (1)

Cathodic reaction:
$$2H_2O \ t \ 2e^- = H2 \ t \ 2OH^-$$
 (2)

Overall reaction: Fe t
$$2H_2O = H_2 t Fe(OH)_2$$
 (3)

Reaction (2) is slow, and thus the overall reaction rate is slow. However, if oxygen is present, an alternative cathodic reaction may occur which is much more rapid than reaction (2):

$$1/2 O_2 t H_2 O t 2e^- = 20H^-$$
 (4)

which, combined with reaction (1), gives the following overall reaction:

Fe t
$$1/2 O_2$$
 t $H20 = Fe(OH)_2$ (5)

The ferrous hydroxide is further oxidized to form rust by the reaction:

$$4Fe(OH)_2 + 2 H_2O + O_2 = 4Fe(OH)_3$$
 (6)

Reactions (5) and (6) are much faster than reaction (3), and steel will corrode much more rapidly in brines containing oxygen than in oxygen-free brines.

The corrosion of steel depends upon the pH, temperature, Cl-content as well as on the oxygen content of the solution. In order to understand this behavior, it is useful to utilize a Pourbaix diagram [H-l]; a thermodynamic stability diagram which is a plot of potential versus pH. Each combinat ion of these variables leads to the formation of various compounds or species which can be mapped to show whether the metal is immune from corrosion, whether it corrodes, or whether a reaction product film forms which may passivate the metal. Figure H-l shows such a diagram for iron at 25°C (steel is essentially iron with some minor add it ions). If the pH-potential combination falls within the iron region (Fe), the metal is immune from corrosion. If the combination falls within the Fe₃O₄ or Fe₂O₃ fields, the iron may become passivated if the reaction product film is impervious and does not continuously dissolve or spall. Lines (a) and (b) represent the stability limits for water, the respective reactions being:

(a)
$$O_2 + 4H^{\dagger} + 4e^{-} = 2H_2O$$
 (7)

(b)
$$2H^+ + 2e^- = H_2$$
 (8)

It should also be noted that the lines for the stability regions depend upon the concentration of dissolved species as shown by the parallel lines for reactions (23) and (28). For example, reaction (28):

$$2Fe^{2+} + 3H_2O = Fe_2O_3 + 6H^+ + 2e^-$$
 (9)

has a potential dependence given by:

$$E_0 = 0.728 - 0.1773 \text{ pH} - 0.0591 \log (Fe^{2+}).$$
 (10)

A low concentration of Fe^{2+} expands the "corrosion" region markedly. The equilibrium potential of $Fe^{-Fe^{2+}}$ is -0.62 volt, which, for a neutral soltition and low Fe^{2+} content, places iron in the "corrosion" region. The Pourbaix diagram will be used to show how pH and chloride content change the nature of the corrosion products.

^{*}It has been shown that the passive films formed on iron are the oxides [H-2,H-3]. However, the Pourbaix diagrams can also be drawn to show the equilibria involving the iron hydroxides instead of the oxides.

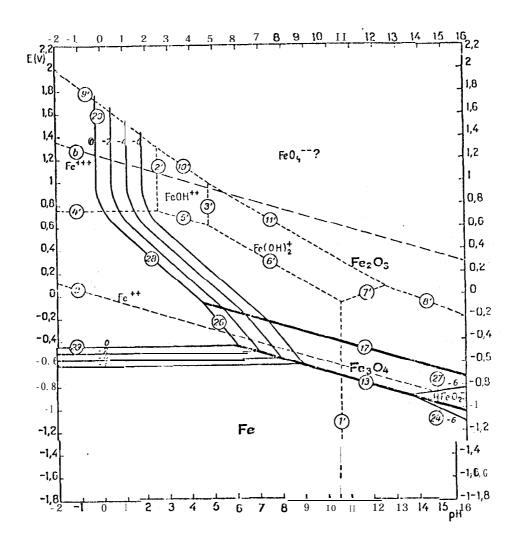


Figure H-1. Potential-pH Equilibrium Diagram for the System Iron-Water at $25^{\circ}C$.

Corrosion is an electrochemical process, and the current is therefore a measure of the corrosion rate. If steel is anodically polarized (held at a given potential during which time the current is measured), the corrosion rate increases with increasing potential until the potential of the passivity region is reached. The current then drops markedly and corrosion is suppressed. The iron remains passivated until much higher potentials are reached at which point the passive film becomes unstable and breaks down locally (the transpassive region). Corrosion then proceeds with further increases of potential. This phenomenon is illustrated in Figure H-2 for five different pH values [H-4]. It may be noted that the passivity region increases with increasing pH. The pH of the brines in the SPR program vary from approximately 6.2 to 7.9 with the exception of Bryan Mound Cavern No. 4 which has a value of 10.4.

Dilute salt solutions have a highly deleterious effect on corrosion by markedly reducing the potential at which transpassivity occurs. This effect is shown in Figure H-3 [H-5] for the same pH values depicted in Figure H-2. The presence of chlorides enables corrosion to occur over a much wider range of conditions than in chloride-free solutions. In other words, the protective nature of product films is lost or greatly reduced in the presence of chlorides.

Reaction (4), oxygen depolarization, controls the corrosion rate in chloride solutions, and thus with the chlorides rendering the passivation films less protective, one expects that the corrosion rate should increase with chloride content. This does indeed occur up to about 3 wt.% NaCl (seawater concentration), but at high concentrations, the rate decreases to values considerably less than for chloride-free water containing oxygen [H-6] as shown in Figure H-4. The decrease results from a significant decrease in oxygen solubility with increasing chloride content.

The increased corrosion rate observed with increasing chloride level in the dilute range results from the increased conductivity of the chloride solution. High-purity water has a low conductivity, and thus anodes and cathodes must be near one another. Hydroxyl ions forming at the cathodes are then always near Fe^{†2} ions forming at the anodes, the hydroxyl and iron ions reacting adjacent to the surface to form an adherent layer of rust which is moderately protective. The high conductivity chloride solutions may have anodes and cathodes which are widely spaced. The ions formed at each electrode can diffuse away and react with each other to form flocculent rust away from the metal surface. This type of rust does not offer any protection, and the dissolved oxygen has easy access to the cathodic areas on the iron surface to cause additional corrosion.

The Pourbaix diagrams represent thermodynamic stabilities and offer nothing concerning reaction kinetics. A compilation of

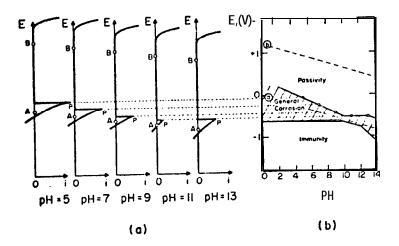


Figure H-2. Behavior of Iron in Chloride-Free Solutions:
(a) Polarization Curves in Solutions of Various pH;
(b) Experimental Conditions of Corrosion, Immunity and Passivity.

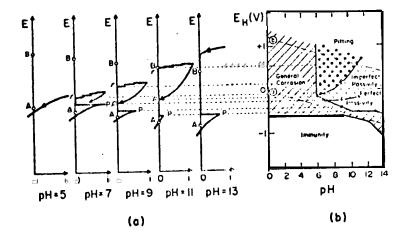


Figure H-3. Behavior of Iron in Solutions Containing 335 ppm NaCl:
(a) Polarization Curves for Solutions of Various pH
(same values as in Fig. 2); (b) Experimental Conditions of Corrosion, Immunity, Perfect and Imperfect Passivity, and Pitting.

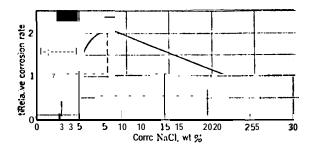


Figure H-4. Effect of Sodium Chloride Content on the Corrosion of Iron in Aerated Solutions at Room Temperature.

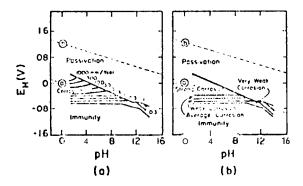


Figure H-5. Experimental Condition of Corrosion, Immunity, and Passivity of Iron in Stirred Aqueous Solutions:
(a) Corrosion Rates; (b) Corrosion Intensity.

rate data [H-8] have been superimposed on the Pourbaix diagram for iron and are shown in Figure H-5 for oxygen-free, stirred solutions. It is clear that low pH and high potential increase the corrosion rate. Fortunately, the pH potential conditions of brine places iron in a region of low corrosion rate, which accounts for the observed long lifetime of steel strings immersed in the brine caverns.

The conclusions reached are that concentrated brines are less corrosive than dilute brines, and that corrosion rates are acceptably low if the brines are oxygen free. The use of uncovered brine ponds, however, introduces oxygen into the brine. Numerous brine strings have lasted over twenty years in concentrated brines, but perforations have occurred during leaching operations (German program) when dilute brines containing oxygen were involved. This potential corrosion problem could affect the SPR expansion program during leaching of new caverns.

Exterior Pipeline Corrosion by Surface Soil Water - Cathodic protection is by far the best means of protecting structural members in corrosive environments, e.g., ships in seawater, pipelines, etc. There is a long history for this technology, and it works well. Referring to the Pourbaix diagram once again, one observes that if the potential of iron in the particular electrolyte can be shifted out of the corrosion region, protection can be achieved. The best means for doing this is shown in Figure H-6 which illustrates three possibilities including cathodic protect ion. Either sacrifical anodes (zinc, aluminum, magnesium) or impressed direct current can be used to cathodically protect the pipe.

This aspect of corrosion has been successfully handled by the petroleum industry for many years by cathodic protection. Present SPR specifications call for cathodic protection, and there should be no problems if accepted practices are followed.

Exterior Downhole Casing Corrosion - Exterior casing corrosion by waters appears to be a sulfide corrosion problem involving dissolved H₂S. The electrode reactions in the corrosion process and their respective potentials are given by [H-9]:

Anodic reaction:
$$Fe = Fe^{2+} + 2e^{-}$$
 (11)

Anode potential:
$$EA = -0.440 + 0.0592 \log a_{Fe}2 + (12)$$

Cathodic reaction:
$$2H^+ t 2e^- = H_2$$
 (13)

Cathodic potential:
$$E_C = 0.0592 \log [H^+]$$

$$- \frac{0.0592}{2} \log P_H$$
(14)

The driving force for the corrosion reaction is the difference between reactions (13) and (11):

$$E_C - E_A = 0.440 + \frac{0.0592}{2} \log \frac{[H^+]^2}{[Fe^{2+}] P_{H_2}}$$
 (15)

The reaction potential depends on the activity of hydrogen and iron ions in solution and the pressure of gaseous hydrogen. The ferrous ion content is a function of the solubility product of ferrous sulfide which is given by [H-10]:

$$[Fe^{2+}][S^{2-}] = 10^{-19} a t 25^{\circ}C$$
 (16)

The sulfide ion content depends on the dissociation constants of hydrogen sulfide:

$$\frac{[H^+] [HS^-]}{[HS]} = 1.15 \times 10^{-7}$$
 (17)

$$\frac{[H^{+}] [S^{2-}]}{[HS]} = 10^{-15}$$
 (18)

Multiplication of equations (17) and (18) gives:

$$\frac{[H^{+}]^{2}[S^{2-}]}{[H_{g}S]} = 1.15 \times 10^{\circ}22 \tag{19}$$

Substituting equations (16) and (19) into equation (15) yields an expression for the corrosion potential when ${\tt H_2S}$ exists in the water:

$$E_C - E_A = 0.353 + 0.0296 \log \frac{[H S]}{2}$$
 (20)

The driving potential thus depends only on the hydrogen sulfide activity and on the hydrogen partial pressure. The corrosion rate increases with increasing hydrogen sulfide content as seen in Figure H-7 (H-11) which also shows the effect of increasing oxygen and carbon dioxide contents. Note the different horizontal scales for each dissolved gas. Taking the maximum values for $\mathtt{H}_2\mathtt{S}$ and the solubility limit of oxygen (about 8 ppm), one can observe

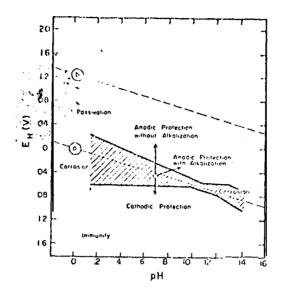


Figure H-6. Various Means of Corrosion Protection for Iron.

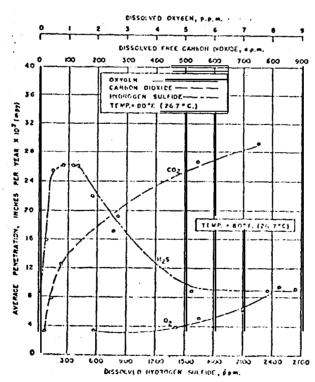


Figure H-7. Effect of Dissolved Gases on Steel Corrosion. Note Different Concentration Scales for Each Gas.

that the corrosion rate due to ${\tt H_2S}$ may be more than three times greater than that due to oxygen, which has previously been shown to be highly deleterious.

Although reaction (20) indicates that the corrosion should be independent of pH, it is not the case as seen in Figure H-8 [H-12]. Corrosion is less at higher pH values. A possible explanation for this effect is as follows. The activities of sulfide and iron ions in a solution saturated with ferrous sulfide and PH $_{\rm S}$ = 1 atm are given by:

$$[s^{2-}] = \frac{1.17 \times 10^{-23}}{+2}$$
[H]

$$[Fe^{2+}] = \frac{[H^+]^2}{1.17 \times 10^{-4}}$$
 (22)

Thus, the ferrous ions are in great excess at low pH values, whereas, at high pH values the sulfide ions are in excess. During corrosion, ferrous ions form at the anodes and diffuse into the solution and sulfide ions diffuse towards the anode. Precipitation of ferrous sulfide forms when the solubility product is exceeded. At low pH the ferrous ions far exceed the sulfide ions, and the few sulfide ions near the anode precipitate out to form ferrous sulfide, and the precipitation zone then moves out into the solution. The net result is that the precipitate does not form a protective film. On the other hand, at high pH the sulfide ions far exceed the ferrous ions, and any ions forming at the anode precipitate out immediately with the available sulfide ions adjacent to the surface. A more protective film results in high pH solutions.

All previous comments concerning corrosion of steel in solutions containing H₂S apply to general (uniform) corrosion. If the corrosion rates for uniform corrosion are well known, it is possible to design systems with a given lifetime on the basis that a known amount of metal will be consumed. On the other hand, localized corrosion occurs in the presence of H₂S in the form of either pitting or stress corrosion cracking (SCC). The localized corrosion is an insidious phenomenon, and it is nearly impossible to predict rates and component lifetimes. Although it is not known, intuitively it would appear that the casing perforations observed by Dow Chemical Co. over the years occurred by pitting corrosion rather than by a uniform attack. Although SCC is well documented throughout the petroleum industry, there is no evidence that SCC has occurred in the chemical industry where brine removal from subsurface domes has occurred.

There are some reasons why SCC has not been observed in brine systems and may not be observed in the SPR program. First, a stress is required which is an appreciable fraction of the yield strength. Generally, the higher the stress, the shorter the time for failure. The susceptibility increases with the strength of material. SCC usually occurs in deep sour wells which exhibit high H_2S levels and which are highly stressed due to the depth of the wells. This is not the case for SPR. The H_2S levels are much lower, and the shallow wells are not highly stressed. Second, the susceptibility to SCC increases with the strength of the steel. The low-carbon steels used in SPR are the weakest steels available and have a low inherent susceptibility. These steels can be made to crack under certain conditions, but these conditions do not exist in the SPR program.

Pitting of steel in H₂S solutions has been studied by Dvoracek [H-13] over a range of pH and potential combinations and for various surface preparations. Slightly oxidized steel, simulating mill scale formed during the processing of pipe, was found to pit in solutions containing 355 ppm of NaCl and saturated with H₂S. The pitting regime is shown on a pH potential diagram in Figure H-9. The pitting potential is independent of pH between 3 and 6. At higher values of pH, the pitting potential becomes more noble, and pitting does not occur as readily as at low pH values. The line delineating the "pitting-no pitting" transition may be explained on the basis of the species present as noted in Figure H-10 [H-14]. The primary species between pH of 3 to 6 is H₂S, whereas at higher pH, the primary species is HS. However, pitting requires the presence of chloride ions. Thus, any spillage of brine around well heads would cause seepage into the ground and would eventually lead to the presence of chloride in the groundwaters. It appears that those salt domes which had been mined previously for sulfur would be most susceptable to pitting of well casings.

The conclusion reached is that acidic groundwaters containing dissolved sulfur species represent a potential corrosion problem, particularly at sites previously used for sulfur recovery. General (uniform) corrosion rates may be three times greater when dissolved H₂S is present compared to dissolved oxygen. The worst possibility is pitting corrosion (highly localized) which has probably caused casings to perforate within two years. Cathodic protection is difficult to utilize. The best way to circumvent pitting corrosion may be to use an alloy steel such as a ferritic stainless which is costly and would require laboratory tests to establish if the required protection can be achieved. Therefore, the use of double casings and cementing as currently planned probably represents the best method of minimizing corrosion. Analyses of deep groundwaters have not been made but should be, to aid in predicting expected life of casing.

<u>Galvanic Corrosion</u> - Each metal undergoes an electrode reaction during corrosion which gives rise to a potential as noted in

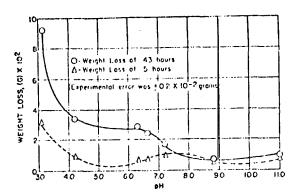


Figure H-8. Weight Loss of Iron Versus pH in an Aqueous Solution Containing $\mathbf{H_2S}_{\bullet}$

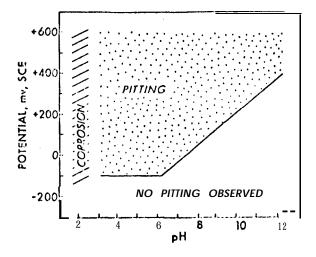


Figure H-9. Potential pH Diagram of Oxide-Coated Steel in Water Containing 335~ppm~NaCl and Saturated with H_2S .

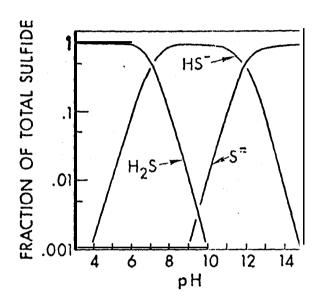


Figure H-10. Distribution of Various Species in Water Containing Dissolved $\mathbf{H_2S}$.

equation (12) for iron. The voltage is measured against **a standard** hydrogen electrode (0.00 volt) and will depend upon the electrolyte to a limited degree. **Some** potentials measured in neutral seawater are summarized in Table H-l.

If two metals having different electrode potentials are electrically coupled to each other, the one occurring above the other in the galvanic series is the anode and will corrode preferentially. The anodic metal will cathodically protect the metal which is lower in the series. The greater the potential difference between the two metals, the greater the driving force for corrosion.

The top of the table represents the "active" metals, whereas the bottom represents the "passive" or noble metals. Note that stainless steels can shift their positions in the series markedly by passivation. If iron and either 13% Cr steel (ferritic stainless) or 304 stainless are coupled, and the stainless is not pass ivated, a small potential difference results (approximately 0.10 volt), and corrosion of the iron will be minimal. On the other hand, if the stainless becomes passive, the potential difference is increased to about 0.80 volt, and corrosion of iron is accelerated.

There are two other factors in addition to the potential differences that determine the extent of galvanic corrosion. These are the relative areas of the anode and cathode and the conductivity of the solution. If the anodic area is small compared to the cathodic area, the current density at the anode becomes very high, and the local corrosion rate of the anode may be excessive. On the other hand, if the cathodic area is small relative to that of the anode, the corrosion rate will be much lower. As far as conductivity is concerned, brine is an excellent electrolyte, and charge transport is no problem. In other words, if a galvanic couple exists in brine, the anodic metal will corrode.

The conclusion reached is that dissimilar **metals** electrically coupled (in intimate contact with each other) will form a battery, and the **most** active will corrode preferentially, especially in brine which is a good electrolyte. Present SPR specifications require isolation flanges which would act as dielectrics. The use of dielectric couplings **between** all dissimilar metals or the use of similar metals throughout will effectively eliminate galvanic corrosion.

The final effort of this corrosion analysis was to investigate site specific conditions relating particularly to the two suspect areas; i.e., inter ior pipeline corrosion by brine and exterior downhole casing corrosion by acidic groundwaters.

Table H-l

Galvanic Series for **Some** Metals and Alloys in Air-Saturated Neutral Seawater

<u>Metal</u>	Potential (volt)
Magnesium	-1.32
Zinc	-0.78
Aluminum	-0.67
Mild steel	-0.40
Cast iron	-0.35
13% Cr steel (active)	-0.30 approx.
304 stainless (active)	-0.30 approx.
Lead	-0.26
Brass (60 Cu-40 Zn)	-0.07
Copper	+0.10
Cupronickel (70 Cu-30 Ni)	+0.34
13% Cr steel (passive)	+0.40 approx.
304 stainless (passive)	+0.40 approx.

Corrosion-Site-Specific Aspects

Discussions were held with personnel from the various sites in an effort to ascertain the conditions existing which could lead to exterior corrosion of well casings. Attempts were also made to obtain some pieces of failed casings or other hardware which could shed some light on the nature of the corrosion. The following discussion considers some of the sites and the problems to be expected in the future, based on past history.

St. James Terminal

Discussions with W. Poarch and T. Sconza revealed that all pipes are coated with epoxy and/or cathodically protected. No caverns are involved at the St. James site. The corrosion problems at this site will involve atmospheric corrosion or soil corrosion for those components contacting the earth. Proper use of standard cathodic protection procedures should reduce corrosion to manageable proportions.

Sulphur Mines

This site is one at which casing corrosion could be severe. According to J. Eggebrecht (DOE) and K. Mills (DUCI) sulfur was previously obtained from the site, and Al 1 ied Chemical Co. had experienced casing corrosion in the 1950's. There is no analysis of water below the surface, but it was stated to be "acid." Double casings will be used, and sulfate-resistant cement will be used to cement the outer casing to the hole wall and the inner casing to the outer casing. Because of the casing length involved (up to 2000 feet) the use of double casings and cementing probably represents the best possible method of minimizing corrosion. Cathodic protection is not feasible. Coatings can not be maintained intact during positioning and during cementing of the casings, and thus, coatings are not recommended.

Weeks Island

This site is rather unique. Mo caprock exists, and the material on top of the salt dome consists of an immediate layer of "moist muck" approximately 2-4 feet thick with about 60 feet of soil on top. The small thickness of material through which casings would extend to the salt cavern as well as the absence of caprock make this site suitable for cathodic protection. A system has been designed, and if properly installed, should adequately control corrosion.

West Hackberry and Bayou Choctaw

R. Mazurkiewicz (SPR) stated that laboratory corrosion tests were made in brines from these two sites. Corrosion rates of 0.01-0.02 inches/year and 0.04 inches/year in brine from West Hackberry and Bayou Choctaw, respectively, were measured. These rates are excessive and may be attributed to dissolved oxygen in the brine. Subsequent tests were made with SO₂ added to the brine as an oxygen scavenger: the corrosion rates dropped to 0.001 inches/year, an acceptable value. Plans are being considered to add SO₂ at the sites, but it is recognized that another problem may be created which is even worse than the one being solved, namely, sulfate-reducing bacteria exist which could result in a sulphidation problem. Inorganic sulfates are reduced in the presence of hydrogen to sulfides which is greatly aided by the presence of an iron surface. The overall reaction results in 3 moles of iron hydroxide and one mole of iron sulfide according to:

$$4\text{Fe} + 2\text{H}_2\text{O} + \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{CO}_3 = 3\text{Fe} \text{ (OH)}_2 + \text{FeS} + 2\text{NaHCO}_3.$$

This is a rapid reaction and has been extensively observed on oil well casings, buried pipelines, deep water wells, etc. The bacteria are anaerobic and could thrive under the dissolved oxygen content and pH conditions existing in the brine. Before large scale injection of SO₂ into the brine is used for deoxygenation, it is imperative that laboratory tests be made to ensure that the sulfate-reducing bacteria do not represent an even more severe problem than that due to oxygenated brine.

<u>Raryanu n d</u>

This site represents another location at which exterior casing corrosion could be severe because of the sulfur present. W. Root and P. Mayeaux pointed out that a previously capped and buried casing had been oozing a sulfur-containing liquid. The top of the casing was reportedly about 12 feet beneath the surface. The casing was exposed and recapped. An attempt was made to inspect this casing during a trip to Bryan Mound on February 13. However, the casing had been reburied and could not be inspected.

A large depository of corroded pipes and equipment was visited by the writer and Mr. V. Barnett for the purpose of selecting various components which could be subjected to a failure analysis. The identity and prior history of the corroded pipes could not be established, but it was possible to make some educated guesses of the prior history of some pieces. Samples of rust plus a small section of a pipe were removed and subjected to laboratory tests and failure analysis at Sandia Laboratories.

Discussion of Failure Analysis

Of the pipes examined, the two larger ones had the visual appearance of "garden-variety" rust which was loose and flaky. The extent of corrosion on the 11 inch and 36 inch pipes was not excessive, the total amount of wall thickness lost to corrosion probably represented just a few percent. This form of corrosion is expected to be caused by relatively benign groundwater, moist atmospheres, etc. The presence of extraneous elements in the rust, such as calcium and silicon is due to either pickup from the corrodant, e.g., groundwater with dissolved cations, or due to the cement in the case of the 11 inch pipe.

Unfortunately, the lack of a documented history for these pipes precludes any firm conclusions with but one exception. There was no evidence of sulfides in the corrosion products. This fact can be interpreted to mean that either the pipes were not exposed to acidic groundwaters containing dissolved sulfur species, or alternatively, if they were, sulfide corrosion did not occur. It is suspected that the pipes were not exposed to sulfur-bearing waters.

The brine pipe was quite different from the other two and was extensively corroded. The piece examined, typical of a very large number of pipes at the depository site, was completely perforated. Although there was a layer of outer rust which flaked off easily, the corrosion products adjacent to the substrate were very adherent. This type of scale is not typical of normal rusting of steel. The protrusion of the scale into the metal, its firm adherence, its dense structure, the presence of two oxidation states of iron all suggest the corrosion of the brine pipe was notably different than the corrosion of the other two pipes examined.

There is an enigma in the constitution of the corrosion products. A small amount of chlorine was present in the loose rust analyzed. There was no chlorine present in the adherent scale directly attached to the substrate. There was a fairly high amount of chlorine present in the corrosion envelope surrounding an internal inclusion. Obviously, the chloride ions play a role, but it is unknown and difficult to rationalize in light of the above observations. To further complicate matters, the service history of the pipe is unknown.

The quality of the steel was poor. The inclusion content is higher than the writer has ever observed. The inclusions are oxides in an aluminum-killed steel which obviously had a very high oxygen content during melting. The inclusions were massive in some cases and may have been connected with the surface. If this situation existed, the preferential corrosion of the inclusion-metal

interface could account for the isolated internal corrosion products as well as for an apparent "seam." The seam could result from either fabrication or by preferential corrosion.

Regardless of the exact corrosion mechanism, it may be concluded that the environment to which the brine pipe was exposed was extremely corrosive, and if anything similar to it exists in the SPR program, problems may be expected. It should also be noted that the pipe was stated to have carried brine at 100°F, and the higher-than-ambient temperature could account for the excessive corrosion. On the other hand, years of massive steam injection into the ground at Bryan Mound to mine sulfur have raised the temperature considerably. Apparently, the temperature is still high, and the same problem could occur presently in brine lines.

Conclusions/Recommendations

A complete analysis was made using suitable electrochemical corrosion principles on the basis of problems and conditions stated to exist at various sites. Two potential problem areas were defined: 1) Corrosion of exterior well casings by acidic groundwaters which contain dissolved sulfur species in the caprock, and 2) Corrosion of brine pipes by brines containing dissolved oxygen.

The use of double casings and cementing as currently planned probably represents the best method of minimizing corrosion due to acidic water in the caprock. No analyses of deep groundwaters exist but should be to aid in predicting expected life of casings.

While concentrating brines that are free of oxygen do not represent a major corrosion problem, using uncovered brine ponds and fresh water for leaching will introduce oxygen. Tests performed for SPR of aerated brines show that unacceptably high corrosion rates can be reduced to tolerable levels by the use of SO2 to deoxygenate the brine. However, the possible reduction of sulfates by anaerobic sulfate-reducing bacteria may lead to even more severe corrosion. No SO₂ injection is recommended unless suitable tests refute the sulfide corrosion problem.

There are various methods being used or considered by DOE personnel to minimize corrosion. These include cathodic protection when feasible, double casings, epoxy coatings, measurement of corrosion potentials from leads installed in pipelines, etc. It appears that the corrosion problem is recognized and that suitable measures are being taken.

Appendix I

Fluid Circulation in Caverns

The fluid circulation field in SPR caverns has been analyzed for several reasons. Among these are the facts that the homogeneity and stability of the crude oil are influenced by the mixing rate, and circulation fields produced as a result of fluid flow into and out of the cavern can potentially exert a localized drag force on the piping. The failure of the brine string in Bryan Mound cavern #5 raised the question of whether vortex drag could have been the cause of the problem and brought attention to the need for understanding the convective and dynamic circulation fields in the caverns. The analysis described in this appendix was performed to obtain an estimate of the stresses induced by vortex drag. The to obtain an estimate of the stresses induced by vortex drag. The results indicate that this effect was not the cause of the problem at Bryan Mound and that an oil inflow rate an order of magnitude higher than the SPR design value would be required to cause stresses capable of damaging brine strings. Details concerning the circulation due to convection currents under static conditions (no flow into or out of the cavern) and its effect on the crude-oil stratification are discussed in Appendix J.

The radial inflows at the end of the brine string which occur during crude oil filling and leaching operations can produce a vortex flow centered at the end of the brine string due to the natural convection circulation fields in a cavern. Since the initial circulation is perpendicular to the brine string, the resulting vortex will produce drag on the pipe and stress the pipe at the closest support point, i.e., the top of the cavern. A preliminary analysis based on a free vortex model (the velocity profile at the limit of high inflow) indicated that very large stresses could be exerted on the brine string. Since this simple approximation (the free vortex model) neglected all losses, of which pipe drag was the most significant, it was necessary to conduct a more complete analysis to obtain an estimate of the forces acting on the brine string. A descr ipt ion of the analysis follows.

The Navier Stokes equation for the tangential velocity component in cylindrical coordinates (see Figure I-l) for steady state incompressible, axisymmetric flow is:

$$\rho u \frac{\partial V}{\partial r} + \rho w \frac{\partial v}{\partial z} + \frac{\rho u v}{r} = F_{\theta} + \mu \left\{ \frac{\partial^{2} v}{\partial r^{2}} + \frac{1}{r} \frac{\partial v}{\partial r} + \frac{\partial^{2} v}{\partial z^{2}} - \frac{v}{r^{2}} \right\}$$
(1)

u = velocity component in the radial, r, direction,

v = velocity component in the tangential, θ , direction,

w = velocity component in the axial, z, direction, $\mu = absolute$ viscosity, and

 F_A = body force (force per unit volume) in the tangential direction.

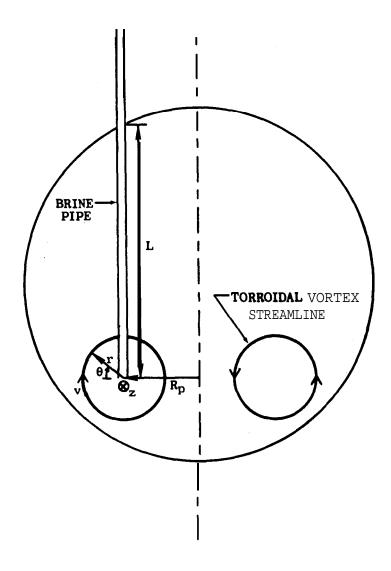


Figure I-l. Geometry and Coordinate System for Vortex Drag Analysis

The presence of the brine string in the vortex flow field causes the flow to be anaxisymmetric. The use of cylindrical coordinates are only approximate due to the curvature of the vortex tube axis (z-direct ion) in the cavern. Cylindrical axisymmetric equations were used to keep the problem tractable. The force exerted on the fluid due to brine string drag is distributed over a torroidal shell with the same radius as the drag producing pipe elements. As a result, all variables were considered to be functions of r alone. The body force becomes:

$$F_{\theta} = -\frac{\rho D C d v^2}{8 \pi^2 R_p r} \qquad (2)$$

where

Cd = coefficient of drag for cylinders (assumed to be 1), and $R_D = distance$ of the brine string from the cavern centerline (ft).

If the tangential velocity, v, is considered independent of z, and the viscous force terms, which are important only for small r (in the core flow) are neglected, equation (1) becomes:

$$\rho u \left(\frac{\partial v}{\partial r} + \frac{v}{r} \right) = -\frac{\rho DC dv^2}{8\pi^2 R_p}$$
 (3)

The core region was assumed to extend several pipe radii (1 foot). The radial velocity, u, was assumed to be of the form:

$$u = \frac{-Q}{4\pi^2 R_D r} \tag{4}$$

where Q is the volumetric flow rate.

Substituting equation (4) into equation (3) and solving for v yields:

$$v = \frac{1}{Cr - C_{\rho}r[ln(r)]}$$
 (5)

where C is an arbitrary constant and $C_2 = C_d D/2Q$. If a reference radius, R_0 , is selected such that drag losses outside of R_0 are negl ig ible, the velocity at R_0 may be estimated to be Γ/R_0 where Γ is the maximum cavern circulation. Equation (5) becomes:

$$v = \frac{\Gamma}{r + C_2 \Gamma r \ln(Ro r)}$$
 (6)

for $r_0 < r < R_0$.

The moment exerted on the brine string about the support point at the top of the cavern, M_{d} , is:

$$M_{d} = \frac{\rho D}{2} \int_{\Gamma_{0}}^{R_{0}} C_{d} v^{2}(L - r) dr \qquad (7)$$

where the contributions of the moment in the core region and the region outside ${\tt R}_{\rm O}$ have been neglected.

Since most of the drag occurs near the end of the pipe, the total drag force was replaced by an equivalent force at the end of the pipe, Feq, having the same moment, i.e.,

$$Feq = \frac{Md}{L} \tag{8}$$

The distributed gravitational restoring force also was approximated by a single force at the end of the pipe, Fg, which produced the same bending moment at the cantilever point as indicated in Figure I-2.

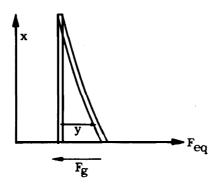


Figure I-2. Br ine String Displacement

The gravitational restoring force, Fg, is given by:

$$\mathbf{Fg} = \frac{\int_{0 \text{ wy dx}}^{L}}{T_{L}} \tag{9}$$

where

w = weight per unit length of pipe $<math>\gamma = pipe displacement from the vertical axis$

The total force on the pipe, P, is given by:

$$P = Feq - Fg \qquad , \tag{10}$$

and the displacement, y, is given by:

$$y = \frac{P}{6EI} (2L^3 - 3L^2x + x3)$$
 (11)

where

E = elastic modulus

I = moment of inertia of the pipe cross section.

Substituting equation (11) into equation (9) yields:

$$Fg = \frac{W}{L} \frac{(Feq - Fg)}{6EI} \int_{0}^{L} 2L^{3} - 3L^{2}x + x^{3} dx$$

and upon integration the gravity restoring force is given by:

$$Fg = \frac{W}{L} \frac{(Fg - Fg)}{6EI} (2L^{4} - \frac{3}{2} L^{4} + L^{4}/4)$$
 (12)

Substituting equation (11) into equation (10) and rearranging yields:

$$P = \text{Feq} \left[\frac{1}{1 + \frac{\text{WL}^3}{8\text{EI}}} \right]$$
 (13)

The total bending moment, M_0 , is given by:

$$M_{o} = PL = \text{Feq } L \left[\frac{1}{1 + \frac{WL^{3}}{8EI}} \right]$$
 (14)

The maximum stress, m, is given by:

$$\sigma_{\rm m} = \frac{{}^{\rm M}_{\rm O}R}{I} \tag{15}$$

where R is the radius of the pipe.

Shown in Figure I-3 is the maximum stress on a 9-5/8 in. diameter brine string as a function of flow rate for several possible values of maximum cavern circulation and brine string length. It is shown that at the range of brine flow rates used for SPR filling and leaching (under 100 MBPD) the stresses are much lower than the yield stress of steel (25,000 psi). It is also shown that the stresses decrease as the pipe length increases (due to gravitational restoring forces) so that no problems are anticipated with the longer brine strings to be used in SPR caverns.

The deflection of a 500 foot long brine string due to vortex drag is approximately 2 feet at 70,000 barrels per day, and the additional pressure drop in the vortex is approximately 5 psi. In conclus ion, it appears that vortex drag will have little impact on the SPE system operation.

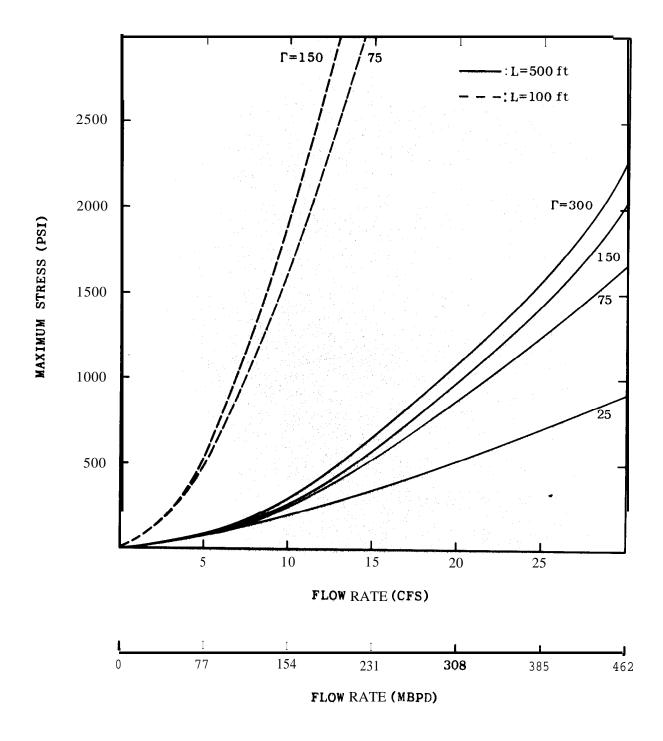


Figure I-3. Variation of Stress Induced by Vortex Drag on a 9-5/8 Inch Diameter Brine String for Several Values of Cavern Circulation, Γ , and String Length, L

Appendix J

Long Term Crude-Oil Physical/Chemical Stability

In order for the SPR to be an effective deterrent against future OAPEC embargoes the recovery and refining quality of the stored crude oil must be guaranteed. The history of storage of crude oil and petroleum distillates in salt environments is short, and as a result, little information is available regarding the physical and chemical properties after prolonged storage. With the exception of the current US SPR effort, only the Federal Republic of Germany and the French Government have stored crude oil in salt environments. The Federal Republic of Germany (FRG) using the services of Kavernen Bau-und Betriebs-GmbH (KBB) have stored several types of crude oil and distillate fuel oils in solution mined salt caverns since 1971. Crude oil and diesel oil are stored in solution mined salt caverns in Manosque, France with seasonal turnover of stocks, i.e., crude oil is stored during summer months, and withdrawn during winter months when demand is high. According to the trip report [J-1] of Richard E. Smith, DOE/SPRPO, the longest period of storage of a crude oil in Manosque was two years. No stability problems have been noted in the French caverns, however, crude oils are not commingled.

The initial United States SPR effort is to store approximately 425 million barrels of crude oil in solution mined caverns (Bryan Mound, TX, West Hackberry, LA, Bayou Choctaw, LA, Sulphur Mines, LA) and 75 million barrels of crude oil in an excavated salt mine (Weeks Island, LA). The different storage mediums present different conditions for the crude oil. Approximate temperature and pressure ranges of the crude oil stored in the oxygen-free solution mined caverns will be 95-113°F and 1000-1500 psi, respectively. The crude oil is in contact with a saturated brine phase in the cavern. The temperature of the crude oil stored in the salt mine is approximately 80°F, at a pressure of approximately 30-200 psi. The crude oil to be stored in the salt mine will be in contact with a vapor atmosphere consisting of oxygen (≈12.5%), carbon dioxide, nitrogen, and hydrocarbon vapors (ethane, butane, propane, etc.). The crude oil will be withdrawn from the solution mined cavern by injecting fresh water into the cavern and displacing the crude oil at the top of the cavern. The crude oil will be withdrawn from the bottom of the salt mine using submersible pumps.

Comparison of the SPR solution mined caverns with the German storage caverns is appropriate. Study of the long-term stability of crude oil is currently being conducted for DOE/SPRPO by KBB [J-2]. The scope of work of the study is to:

- 1. Conduct sampling of oil and brine at various cavern heights at Etzel cavern K-117 and at Lesum caverns L-103 and L-104.
- 2. Perform physical and chemical characterizations of each sample.

- 3. Prepare interpretive reports of the:
 - a. Results of the current analysis with the properties of the oils at the time of storage,
 - b. Degree and stability of emulsion formation,
 - c. Extent of brine dissolution of the oil, and
 - d. Degree of mixing or stratification of the oil.
- 4. Supply a duplicate set of all samples to SPRPO.
- 5. Prepare a comprehensive report of the effects of prolonged storage on the physical, chemical, refining and/or marketing characteristics of the oils.
- 6. Design a computer model for predicting the degree of mixing or stratification of individual lots of crude oil.

The development of a cantilevered sampling device and subsequent sampling of Etzel cavern K-117 and Lesum caverns L-103 and L-104 have been performed [J-3]. During the sampling of caverns K-117 and L-103 viscous fluid phases were discovered at the crude-oil/brine interface. The cantilevered sampling arm could not be lowered into the phase due to the high viscosity: a central sampler had to be used in its place. Preliminary information regarding the physical/chemical characterization of the samples [J-4] from caverns K-117, L-103, and L-104 indicate little variation of the crude-oil viscosity in the vertical direction except in the viscous zone at the crude-oil/brine interface. Samples from caverns K-117 were sent to the Bartlesville Energy Technology Center (BETC) for analysis [J-5] with subsequent transfer of two subsamples (K-117/21, K-117/22) to Sandia Laboratories for chemical and rheologic tests.

Analysis of German Crude-Oil Samples

Rheologic tests conducted at Sandia Laboratories indicate the samples to be non-Newtonian fluids (in non-Newtonian fluids the viscosity is a function of the shear rate). Figure J-l shows the fluid viscosity as a function of angular velocity at various temperatures. The decrease in the apparent viscosity at increasing shear rates (shear rate is proportional to angular velocity) indicates that the fluid is pseudoplastic. At a constant shear rate the apparent viscosity of the fluid decreases from an initial maximum to an equilibrium viscosity indicating a thixotropic fluid.

Highly paraffinic (waxy) crude oils exhibit non-Newtonian fluid properties. Wax particles agglomerate at low shear rates causing an increase in the apparent viscosity. High shear rates break the agglomerated particles causing the viscosity to drop.

Petrellis and Flumerfelt [J-6] state that at low temperatures shear degradable oils exhibit non-Newtonian behavior, but at increased temperatures the oils approach Newtonian behavior. This ef fect

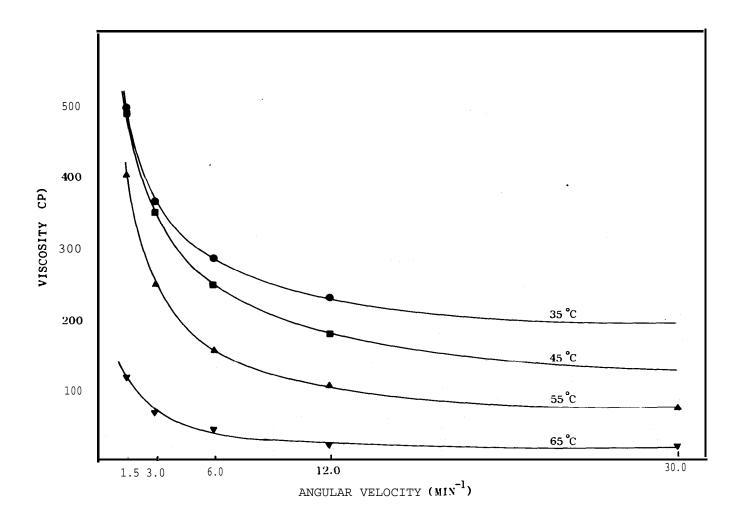


FIGURE J-1. Pseudoplastic Behavior of Sample K-117/22.

is shown in Figure J-l as the "flattening" of the isotherms at elevated temperatures.

Shown in Figure J-2 are the equilibrium viscosities of samples K-117/21 and K-117/22. At 50°C the equilibrium viscosities of samples K-117/21 and K-117/22 were 270 cp and 90 cp respectively, which are much higher than the values reported by KBB [4] (7.7 cp and 8.1 cp for samples K-117/21 and K-117/22, respectively). This discrepancy could be due to the oxidation of the samples during shipment from Germany (similar to the case of aging of coal liquids, see Thomas and Noles [J-7]) or the German measurement may have assumed Newtonian fluids.

Shown in Table J-l are the elemental analysis, water content, apparent molecular weight, ash content, and the benzene soluble/ pentane insoluble fraction of the samples. The benzene soluble/ pentane insoluble fraction of the crude oil contains the asphaltenes and the high molecular weight paraffin waxes. Discussions with BETC indicate that approximately 2% of the samples are asphaltenes, while approximately 9% of the samples are waxes, which agrees with the rheologic data previously described. The average carbon number of the waxes as determined by gas chromatography is approximately C₄₈. The gas chromatograms of samples, K-117/21 and K-117/22 are shown in Figure J-3. Table J-2 is a compilation from reference J-2 of the types of crude oil stored in cavern K-117 with various physical properties tabulated. The crude oils can be described as intermediates, i.e., not paraffinic (straight chain alkanes) nor naphthenic (cyclicparaffins), but somewhere inbetween. samples were distilled using an ASTM D-2887 technique that was correlated back to ASTM D-1160. The distillate comprised approximately 73% and 74% of samples K-117/21 and K-117/22 respectively. Figure J-4 is a normalized distillation curve (based on total distillate) of samples K-117/21 and K-117/22 as compared to crude oil sampled at the bottom (1378m) and the top (1064m) of the cavern K-117, and a sample of Norwegian Ekofisk crude oil. offset of the curves indicates that samples K-117/21 and K-117/22 are higher boiling hydrocarbons than the comparison samples.

The conclusion reached is that the viscous zone is a concentration of the paraff <code>inic</code> waxes in the crude oil, comprising approximately 0.5 volume percent of the storage in <code>Etzel</code> cavern K-117, and not a settling of <code>BS&W</code> (0.05 volume <code>%)</code>, or a water-in-oil emulsion. The concentration of the waxes could be due to a number of effects:

- 1. Commingling of different crude oils in the cavern causing a solvent phase precipitation,
- 2. Interaction between the crude oil and the fuel oil used as a blanket material in cavern K-117, or
- 3. Interaction between the crude oil and the brine phase.

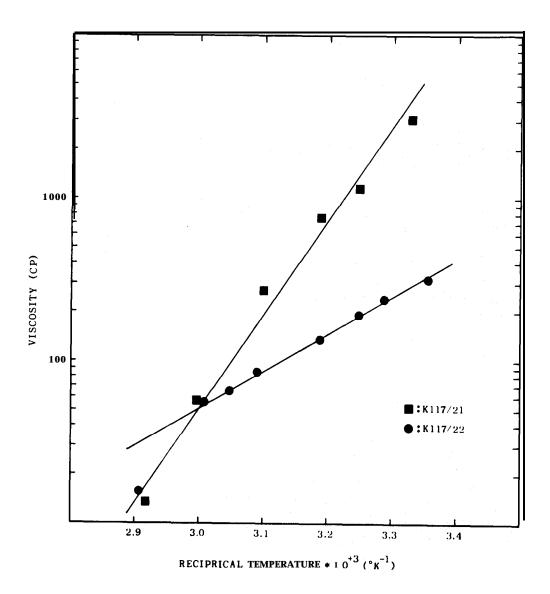


FIGURE J-2. Viscosity as a Function of Temperature of Samples K-117/21 and K-117/22.

TABLE J-1

ANALYSIS OF SAMPLES 21.1 AND 22.1 FROM ETZEL CAVERN K-117

<u>Sample: K-117/21</u>	Sample: K-117/22				
Sample Depth: 1380 m	Sample Depth: 1382 m				
Carbon: 80.96 %	Carbon: 78.28 %				
Hydrogen: 12.61 %	Hydrogen: 12.41 %				
Oxygen: 3.47 %	Oxygen: 5.40 %				
Nitrgen: 0.30 %	Nitrgen: 0.17 %				
Sulfur: 1.86 %	Sulfur: 1.90 %				
H/C: 1.86	H/C: 1.89				
Water Content ^a : 0.84 %	Water Content: 1.64 %				
Apparent Molecular Weight^b: 407	Apparent Molecular Weight ^c : 411				
Ash Content: 1.16 %	Ash Content: 1.47 %				
Benzene soluble/pentane insoluble: 11.28%	Benzene soluble/pentane insoluble: 11.36%				

- a. Karl Fisher analysis
- b. Vapor Phase Osmometry 19.5 mg/mlTHF @ 40°C
- c. Vapor Phase Osmometry 20.2 mg/mlTHF @ 40°C

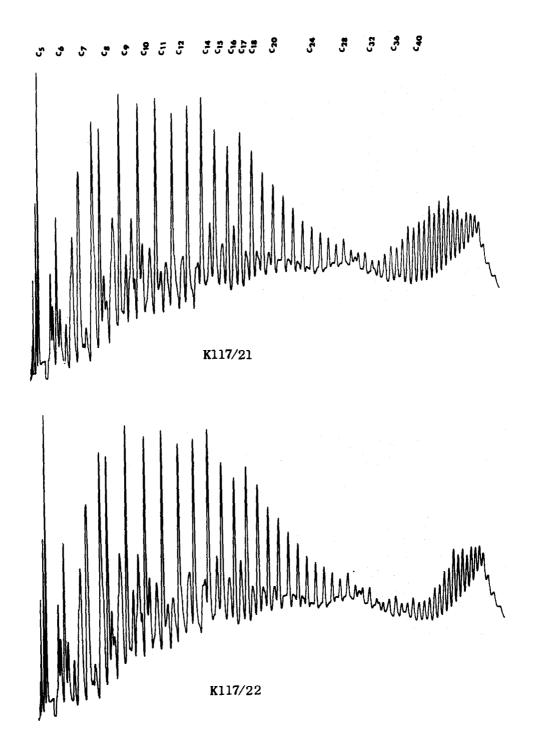


FIGURE J-3. Gas Chromatograms of Samples K-117/21 and K-117/22

TABLE J-2

COMPILATION OF TANKER OFFLOADING REPORTS OF CRUDE OIL STORED IN ETZEL CAVERNS

Tanker	Crude Type	API (60 ⁰ F)	Gravity (15 %)	Water (wt %)	BS&W (vol %)	Viscosity (20°C) (cSt)	Salt (ppm)	Sulfur (wt %)	Vapor Pressure (psi)
World Horizon	Arabian Light	33.51	0.8571	0.1	0.1	9.520	26.7	1.69	4.27
Adele	Iranian Light	33.61	0.8566	0.1	0.05	a	32.4	1.4 ^b	6.5 ^b
Taurus	Iranian Heavy	30.98	0.8704	0.1	0.05	15.53	40.0	1.73	5.12
Sea Swift	Basrah	34.07	0.8542	0.1	0.1	10.19	16.2	1.92	5.83
Golar Toko	Khafji	28.37	0.8846	0.1	0.05	32.42	52.6	2.69	8.11
Daring	Arabian Medium	30.79	0.8714	0.1	0.05	18.70	29.5	2.27	5.40
Gresham	Arabian Heavy	27.71	0.8883	0.1	0.05	37.49	19.0	2.67	6.26
Fair Field Sunrise	Iranian Heavy	30.90	0.8708	a	0.04	18.3 ^b	a	2.51 ^b	4.8 ^b

a. not reported

b. obtained from Oil and Gas Journal, 1976 [J-8]

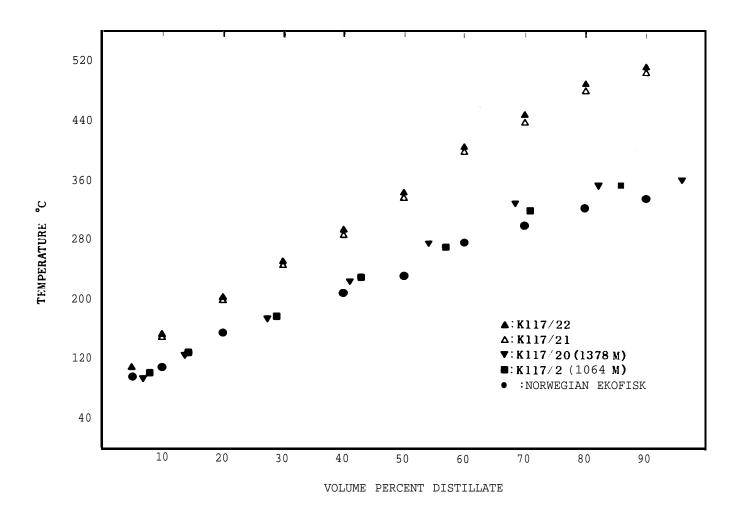


FIGURE J-4. Distillation Curve

The results of sampling at Lesum cavern L-103 seems to contradict presumptions #1 and X2, since only one type of crude oil (Arabian Light) is in storage, and fuel oil was not used as the blanketing material: however, the viscous phase was observed at the crude-oil/brine interface. No viscous zone has been reported (although cavern sampling has not been performed) at the solution mined caverns in Manosque, France, where only one type of crude oil per cavern has been stored which seems to contradict presumption #3 that the brine interface causes the concentration. The explanation of the cause of the wax concentration is beyond the scope of this report. Whether the effect of wax concentration will be observed in the SPR solution mined caverns or salt mine is difficult to determine. Table J-3 lists the anticipated crude oils to be stored at the Bryan Mound cavern site.

TABLE J-3

Anticipated Crude Oil Types Stored at Bryan Mound, Texas

Crude Oil Types	Typical <u>API Gravity</u>	Typical Sulfur wt %	Typical BS&W vol %
U. K. Forties	36.4	0.28	0.05
Libyan Es Sider	37.1	0.38	0.05
Libyan Sirtica	37.7	0.53	0.05
Iranian Light*	33.2	1.29	0.10
Saharan Light	43.7	0.11	0.05
Norwegian Ekof isk	37.7	0.17	0.0

The quantity of each type of oil in each cavern cannot be determined and consequently, predicting the results of the commingling is impossible.

The consequence of a wax concentration in SPR caverns, similar to caverns K-117 and L-103, does not appear serious since crude-oil production occurs at the roof of the cavern. During withdrawal at the SPR sites, certain percentages of crude oil are to be left in the caverns as blanket phases. As long as the viscous fluid remains in the cavern, no problems should be encountered. If the waxy fluid is withdrawn from the cavern, severe pumping

^{*} One cargo of Iranian Light (248,611 bbl - DOE Type I) has been commingled with the DOE - Type V oils.

and piping problems could result due to the non-Newtonian behavior of the fluid and the buildup of paraff inic waxes on the inside of pipes [J-9,J-10,J-11]. The piping and pumping designs at all SPR sites have been based upon the assumption of Newtonian fluids. The consequence of a waxy layer in the salt mine could pose difficulties since the withdrawal of the crude oil will be from the bottom where the higher gravity waxy phase will settle. The large floor area of the salt mine will keep the phase dispersed until crude oil withdrawal is initiated. The suction side of the sump pumps are within an 18 inch diameter pipe that extends to the floor of the mine, and consequently, the crude oil is always pumped from the floor.

Crude oil has been stored in granite caverns in the Netherlands, a coal mine in South Africa, and in an iron mine in France. Information as to the type and quantity of crude oil stored was not found, and therefore, comparison with the SPR storage in salt mines was not possible.

Stratification of Crude Oil

Except for the viscous zone at the crude-oil/brine interface, the crude oil at cavern K-117 was homogenous, which indicates that stratification of the crude oil did not occur in the cavern. Extrapolation of this result to SPR caverns is inappropriate since:

- 1. Cavern geometries are different, which affect the degree of mixing due to thermal convection,
- 2. The degree of stratification will be affected by the physical properties of the crude oil stored, and
- 3. The degree of stratification will be affected by the filling schedule, i.e., the layering of the crude oil in the cavern.

John McKenna of Warren Petroleum stated that liquefied light hydrocarbon gases (butane, propane, etc.) do not mix during storage in salt caverns. In order to homogenize the cavern, gas is produced from the roof of the cavern and reinjected into the bottom of the cavern creating a "turnover" effect. Mixers are also commonly used in crude-oil storage tanks to prevent stratification of the crude oil in the tank [J-12].

In an effort to predict the degree of mixing in the SPR caverns due to thermal convect ion, numerical modeling of the free convection in the cavern was attempted. A cavern was idealized as a right circular cylinder as shown in Figure J-5.

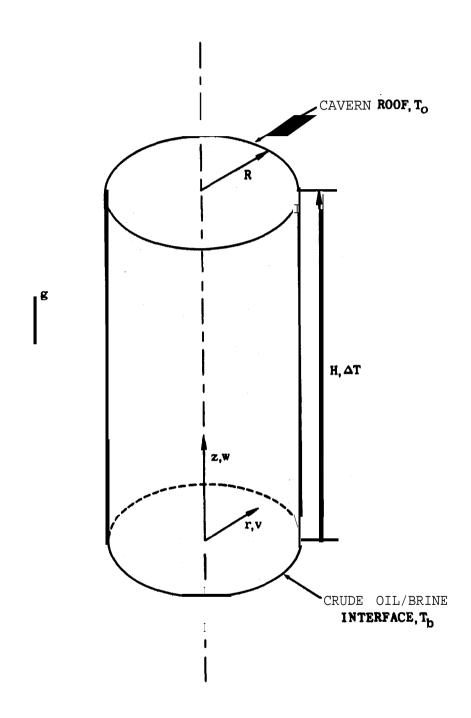


FIGURE J-5. Geometry and Coordinate System for Cavern Thermal Convection

Assuming the Boussinesq approximation (fluid is incompressible except for the temperature effect in the gravity term) the dimensionless stream function and vorticity transport equations in cylindrical coordinates become :

$$-\eta_{\mathbf{r}} = \frac{d^2 \psi}{dr^2} - \frac{1}{\mathbf{r}} \frac{d\psi}{d\mathbf{r}} + \frac{d^2 \psi}{dz^2} \tag{1}$$

$$\frac{d\eta}{dt} + v \frac{d\eta}{dr} + w \frac{d\eta}{dz} - \frac{v\eta}{r} = \frac{d^2\eta}{dr^2} + \frac{d^2\eta}{dz^2} + \frac{1}{r} \frac{d\eta}{dr} - \frac{\eta}{r^2} - Gr \frac{dT}{dr}$$
 (2)

where \psi is the dimensionless velocity stream function such that

$$v = -\frac{1}{r}\frac{d\psi}{dz}, w = \frac{1}{r}\frac{d\psi}{dr}$$

and the dimensionless vorticity η is defined by

$$\eta = \frac{d\mathbf{v}}{d\mathbf{z}} - \frac{d\mathbf{w}}{d\mathbf{r}} \tag{3}$$

The dimensionless variables in equations (1) and (2) are defined by

$$\mathbf{r} = \frac{\mathbf{r}^*}{\mathbb{R}} \qquad \mathbf{v} = \frac{\mathbf{v}^* \mathbf{R}}{\mathbf{v}} \qquad \mathbf{t} = \frac{\mathbf{t}^* \mathbf{v}}{\mathbf{R}^2}$$

$$\mathbf{z} = \frac{\mathbf{z}^*}{\mathbf{R}} \qquad \mathbf{w} = \frac{\mathbf{w}^* \mathbf{R}}{\mathbf{v}} \qquad \mathbf{T} = (\mathbf{T}^* - \mathbf{T}_0)/\mathbf{T}_{\mathbf{w}} - \mathbf{T}_0$$

$$Gr = \frac{gR^3(T_w - T_o)\beta}{\sqrt{2}}$$
 (Grashof number)

where the superscript star indicates a dimensional variable and where:

 T_0 = temperature at the top of the cavern, (^{O}F),

 $T_b = temperature at the crude oil/brine interface, (<math>^{\circ}F$),

R = radius of cavern, (ft)

 $v = kinematic viscosity, (ft^2/sec)$

 $\mathbf{8}$ = effective coefficient of thermal expansion, $({}^{\mathbf{c}}\mathbf{F}^{-1})$,

g = gravitational constant, (ft/sec²).

The dimensionless energy balance equation for the cavern becomes:

$$\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial r} + w \frac{\partial T}{\partial z} = \frac{1}{P_r} \left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$
(4)

where the Prandtl number, Pr, is defined by:

$$p_r = \frac{c_\mu}{k}$$

in which:

 $c_p = fluid heat capacity, (btu/lb_m^{o}F)$,

 μ = absolute viscosity, (lbm/ft sec),

 $k = \text{thermal conductivity, } (btu/sec ft^{O}F)$.

The boundary conditions for the problem are:

$$v = w = 0$$
 at $r = 1$
 $v = \frac{\partial w}{\partial r} = 0$ at $r = \emptyset$ and $z = 0$, H/R.

 $T = 0$ at $z = H/R$
 $T = 1$ at $z = \emptyset$
 $\frac{\partial T}{\partial r} = 0$ at $r = \emptyset$
 $T = \left(1 - \frac{zR}{H}\right)$ at $r = 1$

A literature survey did not reveal any solutions to the problem described above for the range of parameters of interest [brine (Gr \approx 10^{16} , Pr \approx 5) crude oil (Gr \approx 10^{13} , Pr \approx 285)]. Attempts to solve the problem of convection in the brine phase (identical to the crude oil problem except with different physical parameters) with a finite-element code, NACHOS [J-13] designed for convection problems was unsuccessful because of the high Grashof number and large number of grid points required for a stable solution.

In order to obtain an estimate of the convection velocity of the crude oil it was noted that the boundary layer of open-ended cylinders in the laminar flow region were similar to the boundary layer on vertical flat plates for the case $H/R \approx 1$ [J-14]. Assuming that this would also be the case in the turbulent region, the maximum boundary layer velocity of the crude-oil velocity was calculated from the equation [J-15]

$$w_{\text{max}}^* = 0.636 \frac{Gr^{\frac{1}{2}}v}{z} \left(1 + 0.494 \text{ Pr}^{2/3}\right)^{-\frac{1}{2}}$$
 (5)

to be 1.75 ft/sec where **2*** is used as the reference length in the Grashof number. With a boundary layer thickness of 1.9 ft. [J-15], the turnover time (time of one cycle of crude oil in the cavern) was calculated to be approximately five days which indicates that the crude oil in the cavern could indeed be kept homogenous by thermal convection. This evidence is further substantiated by the fact that the temperature gradient in the vertical direction in cavern K-117 is small [J-4] indicating that fluid circulation is occurring in the cavern. It should be noted that the assumption of a right circular cylinder was made in this analysis. This is not the case in many ESR caverns, and as a result thermal convection may be limited due to a reduced temperature difference, and poor circulation geometries (e.g., Bryan Mound cavern **\$5**).

Proposed research by BETC to study the effect of thermal convection on oil stratification in caverns is questionable since experimental design requires the Grashof number of the laboratory apparatus to equal that of an actual cavern, i.e.,

$$G_{\mathbf{r}}' = G_{\mathbf{r}} \approx 10^{16}$$

where $\mathbf{G_r'}$ = Grashof number of bench scale experiment,

 $\mathbf{G_r}$ = Grashof number of solution mined cavern,

which cannot be attained in the laboratory. The extent of stratification of an individual cavern can therefore only be determined by actual sampling of the crude oil at different heights within the cavern.

Biodegradation of Crude Oil

A short term study of the effect of dissolved gases on the solution mining process by PB/KBB [J-16] for DOE/SPR is the only study that has addressed the area of biodegradation of crude oil. The study expressed concern regarding <u>Desulfovibrio desulfurican</u> bacteria. To correctly analyze the problem, two areas actually need to be addressed:

- 1. The degradation of crude oil by aerobic (Weeks Island) and anaerobic (Bryan Mound, West Hackberry, Bayou Choctaw, and Sulfur Mines) bacteria, and
- 2. The reduction of sulfates to sulfides in the crude oil by <u>Desulfovibr io desulfur ican</u> bacter ia resulting in the oxidation of the crude oil. Further reduction of the sulfide cannot be performed by <u>Desulfovibrio desulfurican</u> bacteria.

A voluminous amount of research has been conducted in the field of aerobic biodegradation of crude oils. A general review of the literature yielded studies on the oxidation of alkanes [J-17,J-18] and aromatics [J-19, J-20, J-211. A general review on aerobic hydrocarbon biodegradation is given by McKenna and Kallio [J-22].

Aerobic biodegradation applies only to the case of the salt mine, where oxygen is available in the vapor phase above the crude oil. Bacteria which oxidize hydrocarbons are generally the species of Mycodacteria, Pseudomonas. Nocardia, Corynebacterium, Micrococcus, and Acinetobacter [J-231. The specific hydrocarbon attacked, as well as the rate of degradation, varies between bacteria. The temperature and pressure of the environment also affect the bacteria growth rate. The bacteria does not necessarily need to be halophilic since it does not exist in a br ine phase. The specific bacteria present in Weeks Island Mine, as well as the growth rate of the bacteria should be monitored in order to determine if serious degradation of the crude oil will occur.

The rate of aerobic biodegradation of crude oil is much greater than that of anaerobic biodegradation [J-24]. Hypersaline environments are known to reduce the rate of aerobic biodegradation [J-25], and if this effect is extended to the anaerobic case, the biodegradation of crude oil in the solution mined caverns seems remote. Discussion with D. M. Ward at Montana State University indicated that no evidence exists to rule out anaerobic biodegradation. A possible mechanism for anaerobic biodegradation of n-alkanes as compared to aerobic biodegradation is shown in Figure J-6. The difference between the aerobic degradation mechanism and the anaerobic mechanism is in the first step. The aerobic mechanism involves an oxygenase to convert the alkane to a primary alcohol, while the anaerobic mechanism must convert the alkane to an olefin (alkene) which is subsequently hydrated to the primary alcohol.

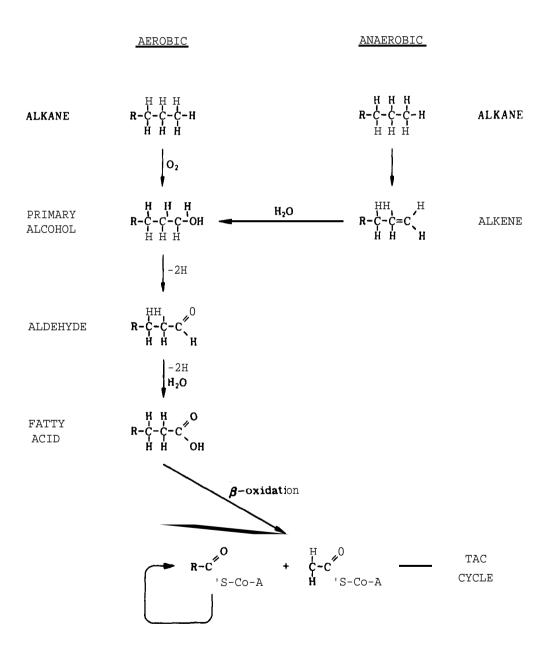


FIGURE J-6: Aerobic and Anaerobic Biodegradation of Normal Alkanes

Anaerobic bacteria that do convert alkanes to alkenes has been described by Parckh, Traxler and Sobek [J-26]. While the probability of anaerobic biodegradation is small, the consequences are severe enough to suggest monitoring the crude oil to guarantee that biodegradation does not occur.

Concern was expressed by PB/KBB regarding the action of <u>Desulfovibrio desulfurican</u> bacteria. **PB/KBB** reports that the bacteria can exist in extreme saline environments (230 g NaCl/l), and "<u>Desulfovibrio</u> are sufficiently well known and feared from the oil fields, since the hydrogen sulfide formed from their reaction with sulp'hate attacks crude-oil production pipelines and storage tanks."

The bacteria is destroyed when exposed to an aerobic environment. This is not to say that the bacteria does not pose a hazard to the stability of the crude oil. Rosenf ield [J-2?] reported rapid destruction of n-hexadecane by the action of <u>Desulfovibrio</u>. Reinvestigation by Updegraff and Wren [J-28] failed to confirm the results, but again the consequences are sufficiently severe to justify crude oil sampling.

Conclusions and Recommendations

- 1. The quantity of each type of crude oil being stored in each cavern and mine should be recorded and sampled.
- 2. The crude oil in each cavern and mine should be sampled periodically so that the physical/chemical state of the stored crude oil is known,
- Continued surveillance of purchased crude-oil should be conducted to ensure specifications are being met with respect to compatibility with site equipment designed for Newtonian flu ids.
- 4. Further contracts by DOE to KBB are recommended to study the dynamic conditions of Etzel cavern K-117 and Lesum caverns L-103 and L-104.
- 5. In conjunction with recommendation (2), if a viscous phase does appear at the crude oil/brine interface in a solution mined cavern, extreme care should be taken not to withdraw the fluid. Contingency measures should be developed as to the proper course of action to follow if performance at Weeks Island is affected by the phase.
- 6. Aerobic sampling of crude oil at the crude-oil/vapor interface at Weeks Island Mine, and anaerobic sampling of crude oil and brine at the crude-oil/brine interface in solution-mined caverns with subsequent bacteria culture development should be initiated to determine if hydrocarbon biodegradation is occurring,

- 7. DOE-designated crude-oil types should be segregated in storage, and $\,$
- 8. The extent of stratification of crude oil in each cavern should be determined to adequately inform petroleum refiners of the expected type of crude oil.

APPENDIX K

Site Withdrawal Analysis

The detailed numerical network analysis of the Bryan Mound site described below was based on the 150 day withdrawal criterion. One result of this analysis indicates that there are numerous combinations of settings of flow control valves at the site, which will result in the same flow and pressure at the metering station, many of which could cause operational problems. This result precludes a simple characterization of the site and reguires a detailed computer model to determine the best internal flow configuration for a given load. Furthermore, detailed analysis is reguired to establish in what sense one flow configuration is better than another (for example, energy efficiency and safety).

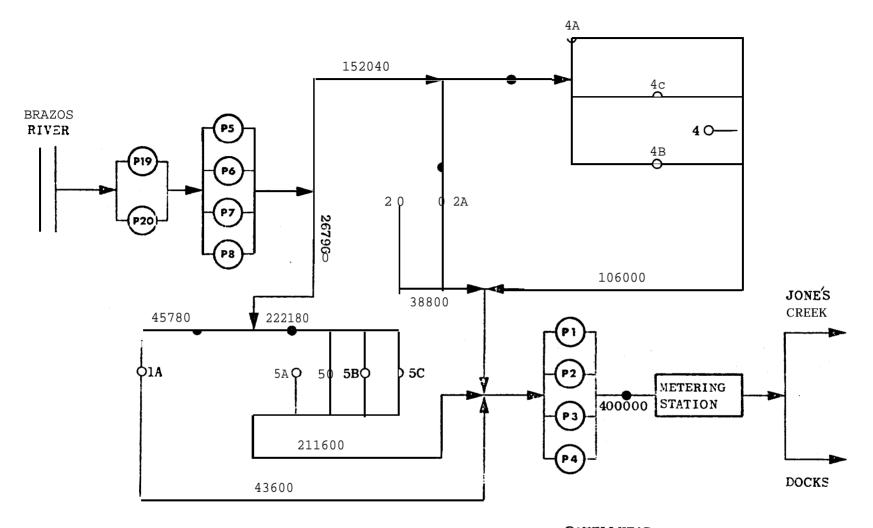
Bryan Round Withdrawal Analysis

The numerical results presented in this appendix were obtained using the network shown schematically in Figure K-l. Pipe lengths, diameters, and locations of control valves were obtained from the Bryan Mound construction blueprints as prepared by S&B Engineers.

The well data used in the analysis was obtained from available documentation and is shown in Table K-1.

Table K-1. Bryan Mound Well Data

Well Number	Casing DiaStringer Dia. (in)	Casing Depth- Stringer Depth (ft)
1A	13 3/8-8 5/8	2200-2840
2	8 5/8-Slick	1410
2A	13 3/8-9 5/8	1410-1650
4	8 5/8-Slick	1520
4A	13 3/8-8 5/8	1520-3120
4B	13 3/8-8 5/8	1520-3120
4C	13 3/8-8 5/8	1520-3120
5	13 3/8-9 5/8	1390-3280
5A	13 3/8-Slick	1390
5B	13 3/8-9 5/8	1390-3280
5c	13 3/8-9 5/8	1390-3280



O:WELLHEAD

●:CONTROL VALVE

NOTE: INDICATED FLOWS IN BPD.

FIGURE K-1. Byran Mound ESR Withdrawal System

Oil heights corresponding to full and empty caverns that were used in the analysis are displayed in Table K-2.

Table K-2. Cavern Oil Heights

Cavern	Full Height* (ft)	Empty Height* (ft)
1	300	10
2	150	10
4	500	10
5	1000	50

Flow rates from each cavern were adjusted so that withdrawal **times** from each cavern would be equal. Table K-3 contains the full cavern crude-oil volumes and the percent of total Bryan **Mound** ESR crude oil contained in each cavern.

Table K-3. Cavern Oil Volumes

Cavern	Barrels of Oil	<u>% of Total</u>
1	6,342,000	10.9
2	5,651,000	9.7
4	15,448,000	26.5
5	30,779,000	52.9
Total	58,220,000	

For a fixed flow rate from **the** Bryan Mound site, the percent flow from each **cavern** for **equal** withdrawal times **must be equal to the** percent of total shown in Table K-3; cavern flow rates calculated by this result were used in the analysis.

Crude-oil flow rates from each well of a cavern were determined as follows. For turbulent flow, the pressure drop, Δp_i across a length, L, of pipe of any cross-sectional shape is given by

$$\Delta p = \frac{fL\rho}{D} \cdot \frac{v^2}{2} \tag{1}$$

^{*}Measured from top of cavern.

where f is the friction factor, ρ is the fluid density, v is the mean fluid velocity, and D is an equivalent diameter equal to four times the hydraulic radius of the pipe. The hydraulic radius denoted by RH is determined from:

$$R_{\rm H} = \frac{\text{Flow Area}}{\text{Wetted Perimeter}}$$
, (2)

where the wetted perimeter is the perimeter actually in contact with the flowing fluid [K-1]. The wetted perimeter, WP, for annular flow is given by:

$$WP = 2\pi R_{CI} + 2\pi R_{SO} , \qquad (3)$$

where R_{CI} is the inner radius of the casing and R_{SO} is the outer radius of the stringer. Similarly, WP for a slick hole is given by:

$$WP = 2\pi R_{CT}.$$
 (4)

The velocity is related to the mass flow rate Q by:

$$v = \frac{Q}{\rho A} , \qquad (5)$$

where A is the cross-sectional flow area. Using the relation-ship for v previously shown, the pressure drop may be written as:

$$\Delta p = \frac{fL}{20A^2} \cdot \frac{Q^2}{D} \tag{6}$$

solving the above equation for Q yields:

$$Q = \left(\frac{2\rho}{rI\Delta p}\right)^3 A D AP = R\Delta p \tag{7}$$

where R is a flow resistance term. Thus, Q is proport ional to the flow resistance for a given pressure drop. The flow resistance R is itself proportional to the flow area A and the square root of D, i.e.,

$$R = K A D^{\frac{1}{2}}$$
 (8)

where K is a constant. This implies that for crude-oil withdrawal from a multiple well cavern for which each well has appproximately the same pipe lengths, friction factor, and pressure drop, the ${\bf flowrate}\ {\bf Q_1}$ from well i is given by:

$$Q_{\mathbf{i}} = K_{\mathbf{l}} A_{\mathbf{i}} D_{\mathbf{i}}$$
 (9)

for some constant K_1 . For an N well cavern the total flow can be expressed as:

$$Q_{N} = K_{1} \sum_{R=1}^{N} A_{R} D_{R}^{\frac{1}{2}}$$
 (10)

Therefore, the fraction $\mathbf{q_i}$ flowing from well i is given by:

$$q_i = A_i D_i^{\frac{1}{2}} / \sum_{R=1}^{N} A_R D_R^{\frac{1}{2}}$$
 (11)

Using the equation shown above with the well data of Table K-I the well flow percentages have been calculated and are shown in Table K-4.

Table K-4. ESR Well Flow Rates

Well Number	Percent of Total Cavern Flow
a 1 11 1.	1000
Cavern l-well lA	100%
Cavern 2-Well 2	61%
Well 2A	39%
Cavern 4-Well 4	26%
Well 4A	24.67%
Well 4B	24.67%
Well 4C	24.67%
Cavern 5-Well 5	13%
Well 5A	61%
Well 5B	13%
Well 5C	13%

The water flow rates into each cavern were calculated by:

$$Q_{W} = 1.05Q_{O}.$$
 (12)

Using the flow rates as determined above, the ESR system was analyzed for the cases of 400 MBPD and 800 MBPD withdrawal rates. The actual ESR design calls for a 388 MBPD withdrawal rate, and the purpose of the 800 MBPD analysis was to identify those components in the system that place restriction on site flow rates.

The analysis proceeded as follows. First, the network as determined from the S&B construction blueprints was modeled, in Figure K-l, which included the cavern raw water and oil flows for the 400 MBPD case. Next, the assumption was made that oil was to be pumped to the Jones Creek Tank Farm with a required pressure there of 100 psig. Using the pipeline curves of Figure K-2 a pressure loss of approximately 40 psig was obtained for a flow rate of 400 MBPD to the tank farm. This required a pressure at the output of the Bryan Mound metering station of 140 psig as indicated in Figure K-3. A pressure drop of 20 psig was assumed across the metering station [K-2] resulting in a pressure requirement of 160 psig at the output of the metering station flow control valves.

According to Ref. [K-3] the crude oil injection pumps P1, P2, P3, and P4 will be used as booster pumps during withdrawal and rawwater injection: pumps P5, P6, P7, and P8 will supply water during withdrawal. The raw-water injection pumps are in series with the raw-water intake pumps P19 and P20 which supply water to the injection pumps from the Brazos River. An offsite oil flow of 400 MBPD requires approximately 420 MBPD of raw water. The pump operating curves for P19 and P20 show that only one of these pumps is required for this flow and that the pump head for this flow is 58 psig [K-4]. The raw water from P19 flows through a 36 inch pipe to the raw-water injection pumps with a calculated pressure drop of 2 psig along the pipe. In order to accomodate a 420 MBPD flow, all four injection pumps P5, P6, P7, P8 are required with a flow through each of 105 MBPD. The pressure rise across each pump for this flow as obtained from the pump operating curves is 600 psig (K-41. Therefore, the pressure at the output of the raw water injection pumps is 656 psig as indicated in Figure K-3. Calculation of the pressure drops along the various pipes leading to the cavern flow control valves were used to determine the pressures at the input to each flow control valve; these pressures are shown in Figure K-3. An important point to note is that for the flow rates under consideration, the losses in pipes leading to each control valve are minimal, i.e., the pressure at the input side of the valve is approximately equal to the pressure at the output of the injection pumps.

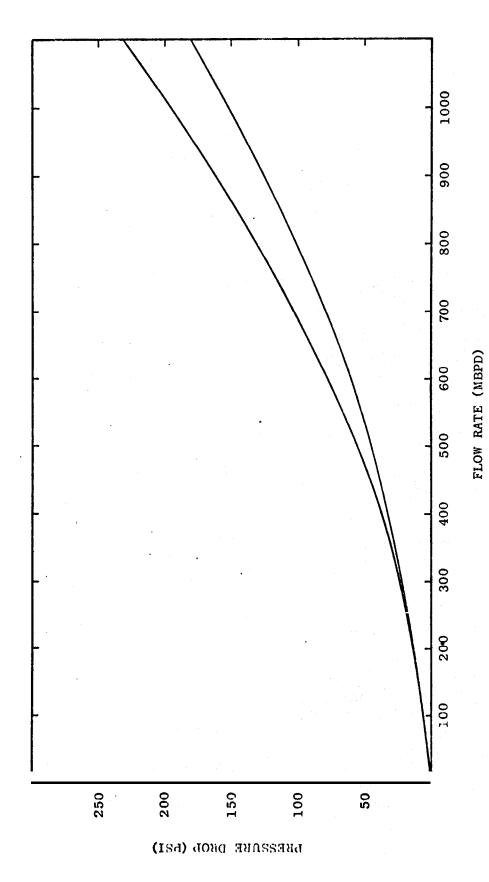
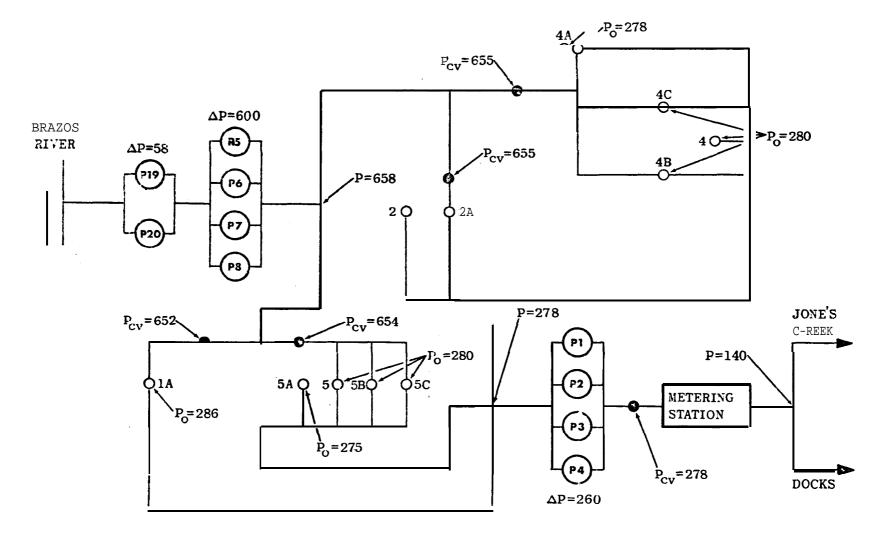


FIGURE K-2. Pipeline Pressure Drops



NOTE: PRESSURES IX PSIG

FIGURE K-3. Bryan Mound ESR Withdrawal System (400 MB/D)

The next step in the analysis was to consider the oil wellhead pressures required for a sustained operation. For the 400 MBPD case it was found that an oil wellhead pressure of 280 psig was sufficient to require a positive water wellhead pressure at all wells.* The oil wellhead pressures are shown in Figure K-3, and are also tabulated in Table K-5 along with the corresponding water wellhead pressures.

Table K-5. Wellhead Pressures

<u>Cavern</u>	Oil Wellhead Pressure (psig)	Water Wellhead Pressure (psig)
l-Well 1A	286	102
2-Well 2	284	Slick Hole
Well 2A	282	144
4-Well 4	280	Slick Hole
Well 4A	278	23
Well 4B	280	23
Well 4C	280	23
5-Well 5	281	67
Well 5A	275	Slick Hole
Well 5B	280	67
Well 5C	280	67

Using the water and oil wellhead pressures as shown, the pressure drops required across the cavern flow control valves were determined and are displayed in Table K-6.

Table K-6. Pressure Drops Across Flow Valves

Cavern	Flow Control Valve	Pressure Drop (psig)
1	c-120-c-2	550
2	c-220-c-2	511
4	C-420-C-2	632
5	C-520-C-2	587

If it is assumed that the crude injection pumps Pl-P4 are bypassed, there will be a 118 psig drop developed across the flow control valves. It should be noted that boosting the oil pressure with

^{*}Positive water wellhead pressures indicate a sustainable operation. When 250 psig was tried for the oil wellhead pressures it was found that the required water wellhead pressure for a full cavern number four were negative indicating the static head would produce flow. This condition is transitory and was not considered further.

these pumps would mean that the pressure would necessarily have to be dropped across the metering station flow valves which would be undesirable. Fur thermore, it should be noted that the SPR Expansion (phase 2) design calls for use of pumps P102-P105 to inject water during withdrawal. These pumps reduce the raw water pressure significantly (200 psig or less rise) and consequently, the crude inject ion pumps may be necessary as boosters in the SPR system. However, this study was directed at the ESR capabilities and did not consider SPR equipment in the analysis.

When a site flow of 800 MBPD* was used, pressure drops of 300 to 500 psig were determined to occur across the cavern flow valves. Calculations assuming near empty caverns were made for the 400 MBPD case and the pressure drops were found to be 15 to 30 psig lower than those recorded in Table K-6. Using the manufacturers flow valve data it was concluded that for the 400 MBPD case all valves will be operating within the cavitation region; this implies a short valve lifetime relative to the required lifetime. Increasing the flow to 800 MBPD (not an ESR requirement) would lower the pressure drops across the valves to levels that are more acceptable in that the operation of the valves is not necessarily in the cavitation region, but the pressure drops would continue to remain uncomfortably high.

There are two additional factors that impact the withdrawal rates, and these are the velocities of the fluids in the pipes and the maximum allowable casing pressures. In neither the 400 MBPD nor the 800 MBPD case were the maximum casing pressures in any well exceeded. The results of the velocity calculations are contained in Tables K-7 and K-8 for both the 400 MBPD and 800 MBPD cases.

<u>Table K-7. Comparison of Raw-Water Velocities and Erosion Velocities</u>
(400/800MBPD)

Well Number	Is Erosion Velocity (12.5 ft/s) Exceeded by Raw-Water Velocity?	<u>Locatio</u> n
1A	no/yes	stringer
2A	no/no	
4A 4B 4c	no/yes no/yes no/yes	stringer stringer stringer
5 5B 5C	no/yes no/yes no/yes	stringer stringer stringer

^{*}It should be noted that the ESR raw water injection pumps are not adequate for this flow rate. The purpose of the 800 MBPD analysis was to identify velocity limitations in the wells and piping.

Table K-8. Comparison of Crude-Oil Velocities and Erosion Velocities (400/800 MBPD)

Well Number	Is Erosion Velocity (13.5 ft/s) Exceeded by Crude-Oil Velocity?	<u>Location</u>
1A	yes/yes	6 in. pipe from well
2 2A	no/yes no/no	6 in. pipe from well
4 4A 4B 4c	no/no no/no no/no no/no	
5 5A 5B 5c	no/yes yes/yes no/yes no/yes	casing 8 in. pipe from well 8 in. pipe from well 8 in. pipe from well

An interesting point to note is that even in the 400 MBPD case the erosion velocity* of piping leading from wells 1A and 5A is exceeded. The reason for this condition is due to the small diameter pipes of short length that lead from each well to a larger diameter pipe. Well 5A is the most serious in that the calculated velocity is twice the erosion velocity. The results of the casing pressure and velocity calculations show that with few minor exceptions the system is adequate for 400 MBPD withdrawal, and some flow in excess of 400 MBPD could be withdrawn without exceeding ESR pumping capabilities which is 550 MBPD.

The pressure drops across the flow control valves present a more serious problem if the **system** is operated using the raw-water injection pumps as the ESR design indicates. The problem with operating the valves in the cavitation region is that their useful life **is quite** short relative to the 150 day withdrawal criterion.

The analysis of the expansion phase of the Bryan Mound complex proceeded in an identical manner. The topology shown in Figure K-4 was used and the pipe lengths were obtained from the BM-22 piping blueprints. Twelve caverns with three identical wells per cavern were used with each well supplying an equal amount of oil during withdrawal. The stringer in each well was taken to be 8 5/8 inch to a depth of 4000 feet and the 13 3/8 inch casing depth was 2000 feet.

^{*}When the fluid exceeds the erosion velocity, cavitation can cause pitting and material loss from the pipe interior. Above the onset of detectable cavitation erosion, the material loss is proportional to the sixth power of the velocity ratio. The erosion velocity depends on the strength of the pipe material and the density of the fluid.

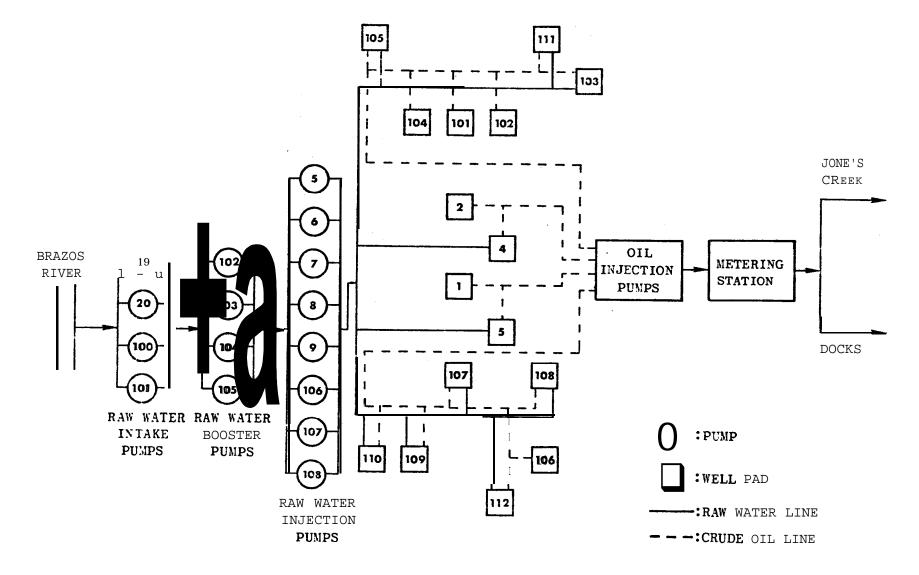


FIGURE K-4. Topology of Bryan Mound SPR Withdrawal Network

Table K-9 contains the results for the case of a 1.02 MMBPD with-drawal rate assuming equal flow from each well and delivery to Jones Creek Tank farm with a 100 psig pressure. This delivery pressure results in an oil wellhead pressure of approximately 350 psig for all wells as indicated in the Table.

Table K-9. Expansion Caverns Withdrawal Results

Cavern <u>Oil Level</u>	Qw (BPD)	Qo (BPD)	Oil Wellhead Pressure (psig)	Water Wellhead Pressure (psig)
Full	29467	20333	350	81
alf _	29467	28333	350	231
Near Empty	29467	28333	350	381

The water wellhead pressures required indicate that for a full cavern the raw-water intake pumps may be sufficient to sustain the initial flow. However, at some point between full and half-full the raw-water booster pumps will be required to sustain the flow: after the halfway point the crude-oil injection pumps will be required. The latter statement follows from the fact that if the oil wellhead pressure were reduced to 190 psig a water wellhead pressure of 220 psig would be required to achieve this and the raw water intake and booster pumps would supply this. However, to obtain the additional pressure required by the load the crude oil injection pumps would be needed as boosters. This analysis illustrates the complexity of system operation and suggests that a more detailed level of analysis is required before operation of the system can be fully understood.

Weeks Island Mine

A limited assessment of the Weeks Island system indicates that the proposed system is sized properly for withdrawal rates up to 590 MBPD. A potential problem area for this site and to a more limited extent all sites is that this site is designed to pump Newtonian fluids and if non-Newtonian fluids are present substantial performance degradation may result. This performance degradation may be explained by considering the equation for pressure drop

$$\Delta p = \frac{fL}{2\rho A^2} \cdot \frac{Q^2}{D} \tag{13}$$

where the terms in this equation are as defined previously. In the case of Newtonian fluids the friction factor can be calculated numerically (or determined from a Moody diagram). The problem with non-Newtonian fluids is that the friction factor may be larger than that for Newtonian fluids. The friction factor for a non-Newtonian fluid can only be determined experimentally. If there is a substantial increase in the friction factor, i.e., larger pressure drops, serious pumping problems are probable.

Additional concerns relating to Weeks Island are: 1) at the highest present permissible flow rates the combination of pump pressure and surge pressure due to valve closure are near the 36 inch pipeline design limits. The addition of two additional pumps as future plans indicate may exceed this limit, 2) in the event of an **onsite** pipe break during fill and power failure there is no single **onsite** valve to. shut off flow: the nearest valve is five miles from the site, 3) there is currently no system available to pump water from the bottom of the mine to a surface disposal area in the event of a water leak in the mine, and 4) sump booster pump maintenance must be performed in the service shaft manifold room. Failure of the hydrocarbon sensing system or ventilation system in the service shaft could create an explosion or fire hazard there. This shaft also connects with and serves as a secondary egress for the Morton Company salt mine and contains an alternate fill line for the oil storage area. A pipe break and power failure while using this fill line could send oil and fumes to the Morton mine.

Based on the findings reported in this Appendix the following recommendations are made:

- 1. The potential problems discussed above should be reviewed and if concurred with, design changes should be implemented,
- 2. In terms of site withdrawal system design, the demands imposed on the site by the external distribution system are of critical importance. The suggested approach is to determine the national oil requirements (by type and location) as a function of the interruption scenario and work back through the major distribution groups to the sites. Thus the load is specified at each step leading ultimately to a site load (or range of loads). Recommended site changes are then based on the anticipated load. This approach attempts to determine and satisfy the actual load, and would also provide a logical basis for turnkey site selection. This emphasizes the importance of the ongoing distribution analysis, and
- 3. In general, there are numerous site operating configurations that can be used to withdraw oil at a given rate. In addition, it is anticipated that rates other than the design maximum will be required. To assist in operating the system safely and economically, it is recommended that a computer model of each site be developed and used by site personnel during withdrawal. This should be an integral part of the operating system of instrumentation, controls, and procedures.

Appendix L

Electrical Power Subsys tern

Electrical power for site operations is purchased from local utilities. The reliability of the service, and distribution onsite is critical to the overall SPR operations. Site electrical drawings [L-1] and supplementary documents [L-2 - L-41 on the technical design criteria and electrical bid packages have be in reviewed in detail. Due to the significant differences in local utilities and site designs, each site design is discussed separately. The electrical site design for Weeks Island was not reviewed in this work.

Bryan Mound

The electrical power subsystem is sized and designed to provide adequate power to the other subsystems with reasonable reliability. Some minor **correctable** deficiencies and comments follow:

- 1. Elementary diagrams of the close and trip circuits for the line oil and 5 kV circuit breakers have been omitted from the drawings. Their existence needs verification.
- 2. Lightning protection of hazardous areas is not specified. Has lightning protection been omitted?
- **3.** Commercial power to the site has a sufficient reliability and short enough repair time to ensure near continuous operation. The capacity of the lines is adequate for site usage. Transformers procured during the ESR are adequate for site expansion.

West Hackberry

Overall reliability of the commercial power appears to be adequate with limitations as detailed below. The actual site distribution design appears to have an adequate capacity, and reliability will be reasonable assuming noted lightning protection exists or will be included.

Site power and, presumably, raw-water pumping power is supplied from a 69 kV, 100 megawatt radial transmission line supplied by Gulf States Utilities- The line is 20-25 miles long from the Caryless substation located between Lake Charles and Sulphur, LA. This radial line is less reliable than a loop scheme, since damage to any part by hurricanes, lightning, etc., will

cause a power outage, possibly for an extended period of time. However, such natural forces are sufficiently remote that reliability should still be reasonable. Additionally, fault protection on the line will limit lightning-caused outages to generally less than one second.

The Caryless substation is served by a loop transmission system; thus, its power source should be good. A spokesman from Gulf States Utilities did note that power to the site could be curtailed during overload periods on the utility power system. This has not occurred historically and is not predicted for the future.

A potentially serious design deficiency, if it exists, is the apparent lack of lightning protection on the primary side of the substation transformers. This is normally covered by the utilities but should be verified.

Bayou Choctaw

The electrical site design at Bayou Choctaw raised some questions which are noted and should be checked. Site power is provided via a one mile radial line tapped from a loop line supplied by Gulf States Utilities. Due to the very limited length of the radial line, the power source should be adequate.

Lightning protection is not shown on the transformer primaries. The utility should provide the protection: this should be verified.

Two 69 kV - 4160/2400 V transformers are shown in the GSU substation in a double-ended configuration. Each will be rated for operation at 7500 kVA self cooled, and 9330 kVA fan cooled. Either transformer is adequately rated to supply the early peak demand of 8500 kVA, but such redundancy will be lost as the load increases to 12,000 kVA projected demand. Proper scheduling of site operations may be a feasible alternative if one of the transformers is out of service: otherwise, additional redundancy may be required.

Most of the design questions arose at Bayou Choctaw due to interconnection of the motor control centers (MCC's), distribution centers (DC's) and other equipment. According to drawing E-15313, MCC-1 supplies MCC-2 which, in turn supplies MCC-12 through DC-1, two transformers and long lengths of cabling. Similarly, drawings E-15313 and E-15314 show that MCC-2 also serves MCC-10 and MCC-11 through DC-2, two transformers, and long lengths of cabling. The reliability of such circuitry may be reduced because of the increased length of cabling involved, and because of the number of electrical components that are connected in series. The designs should be checked with respect to reliability.

Reliability of operation of equipment served by MCC-12 should be checked because of the possible voltage drop. Article 215-2c of the National Electrical Code indicates that feeders should have maximum voltage drop of 3%. In the present series design it appears that a 6 to 10% drop could occur, with the actual voltage drop being dependent on the impedance of all associated transformers and cabling.

Recommendations

Site designs at Bryan Mound and West Hackberry were felt to be qu'te adequate with the assumed verification or completion of the few questions noted previously. Bayou Choctaw appears to have some design aspects that bear further verification. The problems all appear correctable. It is recommended that the designs be reviewed in the areas noted, and if necessary, redesign or modif ication be implemented.

. Appendix M

Pumps and Motors

The major pumps on hand and ordered for the ESR and SPR phases at the four existing sites are Eingham-Willamette (E-W), Peabody Floway (P-F) and Byron Jackson, Motors for the pumps are Siemens Allis (S-A), Louis Allis, Allis Chalmers, General Electric (G-E), Ideal Electric, and Byron Jackson.

Fa t-gathering visits were made to B-W, P-F, S-A, and Power Machinery to obtain detailed information on the major pumps and motors (with the exception of G-E) for the Eryan Mound ESR phase. Visits were made to the Bryan Mound and West Hackberry sites to observe and discuss pumps and motors. Information was obtained from several **DOE** and contractor personnel and reports. Contacts were made with the Bureau of Reclamation in Denver and the DOF Savannah River Plant, both of which operate large numbers of pumps. Emphasis was placed on the Bryan Mound site, but the other sites were also considered.

General Findings

Pumps and motors when properly installed, maintained, and operated are generally very reliable [M-1,M-2]. Information published by the US Nuclear Regulatory Commission [M-3] using normal environment pump/motor data from thirteen different sources gives the following reliability assessments.

Failure Assessment

Event	Median	Lower Bound	Upper Bound
Start failures (per try)	1 x 10 ⁻³	3 x 10 ⁻⁴	3×10^{-3}
Run failures (per hour)	3 x 10 ⁻⁵	3 x 10 ⁻⁶	3×10^{-4}

Reference [M-2] presents data from an analysis performed by a products pipeline company and a major oil company. Pipel ine company results are as follows:

a. 1500 HP, 3600 RPM motor and associated pump

I tern MO tor	MTBF (hours)* 28,783	MTTR (hours)** 32.6
Pump	33,580	25.8
Combined Unit	15,498	29.5

^{*}mean time before failure
**mean time to repair

b. 200 HP, 1180 RPM motor and associated pump

<u>Item</u>	MTRF (hours)*	MTTR (hours)**
Motor	45,552	8.0
Pump	28,470	10.0
Combined Unit	17,520	9.2

^{*}mean time before failure

The oil company has operated 16 B-W pumps with 1500 HP, 3600 RPM Westinghouse motors a cumulative total of 735,840 hours with no motor failures: MTBF for the pumps is 1576 hours; and MTTR for the pumps of 2.5 hours. The relatively low MTBF's are attributed to seal failures, which account for about 90 percent of the failures and are in turn attributed to brine service and impact starts. The pipeline company MTBF results are in agreement with the run failures of Reference [M-3]. The oil company MTBF results, while considerably lower, are indicative of relatively minor failures requiring MTTR of only 2.5 hours.

No manufacturers contacted had compiled data from which numerical values of reliability and maintainability for their product could be obta ined. However, B-W provided approximate numbers of first-year failures following delivery of 3000 pumps and S-A provided failure results for one year's operation of 300 motors of the type used at Pryan Mound, both of which indicate general agreement with the run failure results of the above tables. The Savannah River Plant provided results [M-4] on the operation of eighteen B-W pumps with A-C motors over a period of 25 years which indicate lower failure assessment values and higher MTPF values than those of the above tables. The Eureau of Reclamation in Denver, which operates large numbers of irrigation pumps, has made no reliability assessment, but did state that a breakdown is rare. They consider pump life to be 30 to 50 years.

The extensive difficulties in initial operation of the S-A motors and B-W pumps at West Hackberry [M-5 - M-81 might indicate the possibility of serious basic deficiencies in the products which would limit their reliability. Such does not appear to be true. The major problems included: 1) loss of labels and subsequent erroneous relabeling of terminal wires from the motor, 2) settling of piping connected to the pumps, 3) motor and pump shaft oscillating in an axial direction due to operation with too little flow, 4) loss of adequate pump suction pressure because of a plugged strainer, 5) erroneous signals from pump and motor temperature and vibration sensors and pump suction pressure sensors, 6) excess oil flow to the motor bearings, and 7) failure of mechanical shaft seals on the pumps. Of these problems, only the latter three can be considered problems related to eguipment deficiencies.

^{**}mean time to repair

These have been corrected such that several weeks of essentially trouble free operation have been achieved. Pumps and motors by the same manufacturers and of the same types as those at the West Hackberry site were put into operation at the Bayou Choctaw site with much less trouble and are operating satisfactorily. Visits to the B-W and P-F pump and the S-A motor manufacturer plants indicate the pumps and motors are quality products [M-9]. The reputation of the other pump and motor suppliers should lead to products of similar quality. There is no reason to suspect that the pumps and motors on hand or ordered for the ESR and SPR programs are of lesser quality than those used in the above reliability assessments. It is therefore concluded that the pumps and motors are capable of providing adequate reliability.

All pump and motor experts consulted have emphasized the importance of proper installation, alignment, maintenance, and operating conditions to the satisfactory performance of such units. The manufacturers have provided instruction manuals which adequately describe procedures for inspecting, installing, aligning, and maintaining the units [M-10 - M-141. All pumps and motors should be carefully prepared for storage. When horizontal pumps have been stored for 6 months, bearing housings should be disassembled and shaft and bearings carefully inspected for rust before installation. Horizontal pump motors in storage or not being operated should be rotated 10 revolutions once each month to ensure that the shafts and bearings are bathed in oil. Before installation, pumps and motors should be carefully inspected for any visible damage, for the presence of any foreign materials, and for electrical resistance of the motor windings. The units should be rigidly mounted on rigid pads to minimize vibration. Piping to the intake and discharge of the pump should be supported and arranged to minimize stress on the pump housing due to settling or thermal expansion or contraction of the pipe. Excessive stress on the pump housing will cause misalignment with resulting vibration and excessive bearing wear. In-line and concentric alignment of the motor and pump shafts is very important in that misalignment causes vibration. Maintenance of proper lubrication is obviously essential. Once the units are installed and operating properly, the major maintenance required is lubrication; visible inspection for proper operation, signs of damage and cleanliness; and proper repair at early signs of trouble. When the pumps are not in operation the space heaters in the motor enclosures should be on at all times to prevent condensation of moisture.

The units are equipped with motor and pump vibration, bearing temperature, and motor winding temperature sensors. Any excessive indications from these sensors will cause automatic shutdown of the pump. B-W felt that more sensitive vibration sensors would be a visable. Each pump is also equipped with a sensor to detect net positive suction head and to shutdown the pump if the value is too low. Possible operating conditions which could cause damage and for which no adequate safeguard is provided is operation at less than 30 percent or more than 120 percent

of flow at maximum efficiency. The low flow condition has occurred at West Hackberry because the brine disposal wells would not accept adequate flow. The brine in the pump overheated and vaporized, causing pump shaft thrust imbalance and consequent axial shaft motion. Conversely, the high flow condition would be caused by inadeguate restriction to the flow downstream of the pump. The effect of this condition is to increase the motor horsepower requirements and possibly to reduce the net positive suction head below acceptable values.

At West Hackberry, several failures of the brine pump shaft seals Analysis of these failures indicated the brine being pumped which was used to flush the seals, precipitated salt crystals on the seal surfaces during idle pump times. pump was started, these crystals scored the seal surfaces and caused leakage. As a result, a decision was made to use fresh water for flushing the seals of all the horizontal pumps (brine, oil, and raw water). Clean fresh water flushing has alleviated the brine pump seal problem at West Hackberry and should be effective for all the pumps, particularly if flushing is continued during pump idle periods. Since a source of clean fresh water for the seals was reouired, it was also decided to use the same source for pump bearing cooling. While perhaps not essential, this eliminated the possibility of pump bearing cooling lines becoming plugged by salt precipitated from brine or from particulates in the crude oil which are not removed by the centrifugal separator. It does present additional problems of a source of clean fresh water, additional water pumps and plumbing, and concern over possible freezing in the fresh-water supply system. Also as a result of the seal problems at West Hackberry, consideration is being given to the replacement of carbon wear rings in all horizontal pumps with bronze or brass. This has been implemented on some pumps, apparently with no deleterious effect to date, but probably should be researched further before general implementation.

All sites have at least one spare pump in place for each major pumping function. Assuming the pumps are installed, operated and maintained in a manner to yield reliability as previously discussed, the probability of two or more pumps failing during a short time interval would be remote and a single pump failure should be of little consequence for ESR or SPR. Power-Machinery in Houston, which supplied brine-well disposal pumps for the Bryan Mound site under lease, specializes in repair on a crash basis of pumping equipment for the oil industry. If replacement parts are available, they can change out the rotating assembly and replace all worn parts of any Bryan Mound pump in ten hours. If replacement parts have to be made, additional time up to 1 1/2 weeks is required. If the pump drive motors are burned out or otherwise damaged, it can be rebuilt in about three days by a local electric motor rebuilder. S-A would require about two weeks for factory quality repairs of their motors in their Hous ton shop.

An adequate **stock** of spare parts for the pumps and motors is required to maintain the equipment in good operating condition and to expedite repairs in the event of an emergency breakdown. Although the various sites generally have pumps and motors from the same manufacturers, they are generally different models with the consequence that needed spare parts are different. The status of spare parts for the different sites has not been determined in detail. For Bryan Mound ESR, B-W supplied their recommended spare parts for horizontal pumps, but P-F did not receive an order for vertical-pump spare parts.

One general factor of concern is that the sites are in locations Trequently subjected to hurricanes. Even though pump motors are in Weather Protected II enclosures which require three direction changes of the cooling air of at least 90° before it reaches the rotor and stator, hard driving rains during hurricanes might be expected to result in some water infiltrating the motor and causing damage. If conditions were bad enough to damage one motor, the probability is high that several motors would be damaged. The effect on ESR and SPR could be very detrimental. Hurricane conditions can certainly not be considered a normal environment and could negate the applicability of the previously discussed reliability results.

Specific Findings

The pump ratings at Bryan Mound are adequate to allow the following modes of operation:

- 1. Oil injection in ESR and SPR with brine disposal to the gulf at a rate of 240 MBPD,
- 2. Oil injection in ESR and SPR with brine disposal to wells at a rate of 168 MBPD,
- 3. Oil withdrawal in ESR at a rate of 387 MBPD,
- 4. Oil withdrawal in SPR at a rate of 1,020 MBPD, and
- 5. Raw-water injection for leaching SPR caverns at a rate of 720 MBPD with brine disposal to gulf or at a rate of 168 MBPD with brine disposal to wells.

At Bryan Mound the raw-water injection pumps required for oil withdrawal in ESR are actually second stage pumps for high pressure injection during leaching operations, and are not well suited for withdrawal because of their high discharge pressure. The crude-oil injection pumps, which are scheduled for use as booster pumps during oil withdrawal, may not be required for this function.

At Bryan Mound, there is apparently no booster pump to provide the required net positive suction head for the blanket-oil pumps to be used during the leaching operations. The booster pumps at the oil storage tanks are too large in that each has a capacity eight times that of the largest blanket-oil pump.

At Bryan Mound, the four raw-water intake pumps are fed through a single Motor Control Center "C" located at the raw-water intake structure. A fault in the main 5 KV switchgear, the bus of MCC "C", or in the single 5 KV cable to MC "C" will result in complete loss of raw-water intake for oil withdrawal or leaching. Power distribution for the other pump motors is arranged so that no single point failure will cause loss of all pumps for any given function; raw-water injection, brine to gulf disposal, or oil injection [M-15].

The NEMA code recommends that when non-explosion proof motors such as those of ESR and SPR are used in an environment where a failure such as an oil line leak could result in the presence of flammable vapors, motors should limit surface temperatures of windings, rotors and space heaters to 80 percent of ignition temperature of any gas or vapor which might enter the motor [M-15].

Lightning arrestors are installed on the feeders to each bus in the main switchgear of the power distribution system of the pump motors. Maximum protection from lightning would be obtained by providing surge protection at each motor.

Recommendations

The following are general and specific recommendations regarding ESR and SPR pumps and motors:

- 1. Investigate the possibility of water infiltrating critical parts of the pump motors during hurricane conditions and if not remote, provide adequate protection.
- 2. Investigate the possible explosion hazard in the event of an oil line leak in proximity to the non-explosion-proof motors.
- 3. Consider surge protection at each motor for maximum protection from lightning.
- 4. Review the power distribution to the raw water intake pumps at Bryan Mound (loss of all pumps due to a single point failure).
- 5. Install flow monitoring sensors on each pump to provide indications a) that the pumps are operating within satisfactory flow limits, and b) of decreasing pump flow over a period of time (indication of internal seal ring wear) (see Instrumentation and Control Appendix).

- 6. Establish program to accurately measure and record periodically the vibration of each unit. Increased vibration is a sign of bearing wear and need for repairs.
- 7. Perform an analysis to determine spare-parts requirements for all sites and obtain the appropriate inventory.
- 8. Train personnel responsible for operation and maintenance in factory-recommgpded operation and maintenance procedures,
- 9. Have factory representatives inspect pumps and motors and their installation **prior** to start up.
- Maintain a detailed log for each individual pump and motor.

Appendix N

Site Instrumentation and Control Subsystem

Site instrumentation and control have been reviewed by considering several areas. These are:

- 1. Completeness of Documentation
- 2. Emergency Shutdown Capability
- 3. System Operation
- 4. Component Protection
- 5. Flexibility
- 6. Controllability
- 7. Reliability (Řepairability)
- 8. Complexity

In addition to existing design instrumentation drawings [N-1], documents [N-2,N-3], and proposals [N-4,N-5], detailed discussions were conducted with the design architect and engineers, SPR project staff, site managers, and the current instrument and control contractor (ICS) for the cavern sites. Bryan Mound was reviewed in the greatest detail, hence most specific comments reflect the work at that site. Drawings at the other sites were reviewed to establish the similarity of instrumentation between sites. No work has been done in this area on Weeks Island. The instrumentation contractor for Weeks Island was only recently selected and some similarities between Weeks Island and the other sites are clear, but differences may exist.

System Description

The current instrumentation and control system performs a series of measurements, checks measurement results, alarms when anomalous results are obtained, displays cur rent status and recent history of system variables, provides the capability to control all system operations, and maintains a record of all controls and readings.

System Assessment

In general, the instrumentation and control system appears well designed, and reasonable for the SPR. Deficiencies, errors, and items which could be improved have been identified in several areas; however, the total magnitude of these is only a fraction of the instrumentation and control system effort. Many of the items noted have been discussed with the SPR project staff, and appropriate action taken. Inclusion of the items in this report reflects the overview role of this effort.

The recommendations for future changes and/or additions are felt significant to the success of the SPR. Considerable effort remains in the ESR instrumentation build and installation, and only the A & E designs have been completed for the expansion phase.

A short assessment in each area reviewed is provided. Apparent problems are noted in several areas. These are:

- 1. The documentation is not complete, therefore, only the Bryan Mound BM-9, and BM-23 drawings were reviewed in detail. Problems noted include:
 - a. Drawings issued in February reflect changes through the previous December. On both drawings, Well #1 does not exist although SPR staff plans include a Well #1. Drawings detail instrumentation for four brine well injection pump units although eight units have been ordered.
 - b. Several errors in the drawings were noted. For example, 11 pipelines extend from the match line on I-38702 while 13 pipelines extend from the same line on I-38703 [N-1].
 - C. Drawings specify no instrumentation on the brine disposal wells, although the high pressure brine disposal pumps are instrumented and the gulf brine disposal permits specifies that only brine in excess of the well capability may be discharged to the gulf.
 - d. All drawing revisions have the same number, and updates are only shown by notes. There is no obvious method for ensuring any given drawing is the current revision. Several drawings furnished for this review by the project staff were obsolete, and this fact was unknown to some project staff personnel at the time.
 - e. Nowhere within the drawing package are variable ranges, gauge ranges, etc., discussed, referenced, or companion documents noted.
 - f. No drawings show the signoff signature of a SPR project officer. On many lists there are columns for SPR checker initials and KBB checker initials. The total absence of initials could imply no one has checked the drawings.
 - g. The PB/KBB Bryan Mound Designer Concept Operating Manual requires rework, because it contains errors, followed by a careful review by the designers and SPR before use. PB/KBB expressed the viewpoint that the document was requested and delivered prior to completion of the design, hence later design changes were never incorporated,

- 2. The Emergency Shutdown Capability of the design appears adequate. Automatic shutdown is initiated by the controller for many faults with local manual backups provided.
- 3. System (Instrumentation) Operation has not been accomplished. The conceptual operations manual is poor (noted earlier) and manuals have not been delivered yet by the instrumentation contractor (ICS). It appears that ICS will provide all documentation on how the system operates and can be maintained. The site operations contractor, DUCI, will be tasked with the assignment of producing operating manuals.
- 4. Component Protection is provided for all pumps, tanks, wellheads, and brine ponds. Two additional variables have been identified which would be useful.
 - a. The flow (relative) from each large pump unit should be monitored. This would indicate internal seal leaks and permit early warning of failures and maintenance requirements.
 - b. The pressure differential across flow control valves should be monitored and alarmed. Flow control valves will fail if excessive pressure drops (possible in the ESR system at least) are allowed to occur for a period of time.

Other component protection appear reasonable, and the alarm system which indicates danger and provides automatic shutdown should protect system elements.

- 5. Flexibility is a maximum in the system design. Changes can be accomodated with a minimum of cost or redesign. The most severe limitations are due to the custom circuits, although the number of spare channels appears adequate.
- 6. Controllability as intended is to be a one-man single point control for each system. While designed so that this is theoretically possible it may not be a reality. There are three points to be noted:
 - a. Flow control is set at the input flow side of caverns or at the metering station. Pressure drops within the system result from the pump pressures, flow valves, and piping losses. Controllability of these pressure drops is limited although flow routing is adequate.
 - b. The interlock system prevents an inadvertent system configuration whereby a component will be immediately damaged. There is nothing in the design to indicate inefficient operation or prohibit actions which will overpressure valves or cause fluids to exceed crosion flow velocities.

- c. The controller operates by coded commands, i.e., 409 signifies pump BMP 38 turnon, etc. A suggestion by ICS to use alpha numonic commands, i.e., BMP 38 ON would necessitate more software but simplify the command structure and help avoid mental errors.
- 7. Reliability or quality of the instrumentation and controls has not been specified by SPR or determined in a quantitative manner by ICS. There is no redundancy in any portion of the instrumentation except for a nominal four hour UPS power system. Mil spec parts have been used in the assembly of circuit boards and all systems are readily accessible for repair. Repair will be accomplished via component replacement, and supposedly spares will be stocked although no hardware has been ordered. The present approach to achieve reliability appears reasonable.
- 8. Complexity of the instrumentation and control subsystem is felt appropriate. The system will perform all functions required, is flexible, and without excessive frills. The hard-copy printouts and permanent records maintained within the controller are necessary as permanent records of the site operation.

Recommendations

All deficiencies previously noted can **be** corrected with a minimal of changes and redesign. Specifically:

- 1. The drawing system should be upgraded. Proper signof f authority and check authority should be established. All drawings should have a revision number, updated with any revision, and a master list showing the latest revisions should be available at all times to all program groups.
- 2. Other manuals should either be corrected with appropriate marking to indicate the corrections, or all copies of the documents discarded.
- 3. System operation manuals detailing system operation instructions and anticipated instrument readouts for all configurations should be written as soon as possible. It is important that these be thoroughly reviewed by design, operations, and instrumentation personnel.
- 4. Sonic flowmeters should **be** installed if possible on the output of all large pumps. It is not necessary to have highly accurate readings as long as relative (over time) readings can be obtained. It is reasonable to have local readouts only.

- 5. The pressure drops across all flow control valves should be monitored and (if excessive) alarmed in the control room.
- 6. All ramif ications of implementing noncoded commands have not been addressed. The concept appears useful but the complexity and hardware adequacy have only been discussed briefly. The concept should Be further explored and all tradeoffs evaluated before a judgement is made.
- 7. Little documentation exists on the requirements for a SPR control command and control/monitoring system. ICS has drafted a letter dated 2/5/78 to D. Maaur [N-6] suggesting some work be initiated, The site hardware is adaptable to any mode of operation. Some additional hardware and software will be needed if additional monitoring or command capability is desired.
 - The rationale for the! decision which will establish any central command or monitoring system must be developed. Questions as to how tha system will be operated, what level of SPA staff will be required, etc., must be answered. We recommend that the necessary questions be answered and a policy decision be made, from which any necessary hardware or software additions can be implemented.
- 8. While not an instrumentation problem as such, it appears that the site operators will have to be highly skilled and well trained. Manipulation of valves, pumps, and monitor equipment is within the scope of a single operator, but the level of understanding that will be required to respond to any non-standard mode, i.e., alarm situations, etc., will require highly trained operating personnel. Some consideration as to support for the controller via either dedicated engineering staff or a more sophisticated computer capability should be given.
- 9. Instrumentation for turnkey site proposals should be designed similar to other sites to facilitate operation, maintenance, and an eventual possibility of linking all monitoring and/or control to a central facility.

APPENDIX 0

Long-Term Monitoring of State-of-Health

To insure the long term availability of the quantity and quality of the stored strategic petroleum reserve, an ongoing monitoring effort must be planned. The effort must identify all potential problem areas, provide an ongoing technical assessment of their severity and/or probability of occurrence, and establish a course of action in the event a major problem is predicted and/or occurs.

Within the technical scope of the SPR, long-term problems are those which could effect the quantity or quality of the crude oil and the condition of the storage medium. This has been further delineated as oil accountability, crude oil stability, and cavern integrity.

Oil Accountability includes the establishment of the crude-oil availability and periodic verification, if necessary, of the quantity stored. The current program provides for crude oil to be metered at the dock and after construction is complete, at the site upon arrival (0.1 percent accuracy). From the metering station, the oil is eventually routed to one or more storage caverns or in the case of Weeks Island, into the mine. At the sites using leached caverns, if oil is transfered to more than one cavern simultaneously, the cavern flow meters provide a 0.5 percent accurate accounting.

Current plans include no further periodic check of the quantity of stored crude oil until withdrawal. This assumes that once crude oil is stored in underground caverns, it is secure. It also assumes that the estimates made from sonar surveys of the blanket oil and oil lost in inaccessible cavern roof areas are accurate or at least tolerable. Unfortunately, the amount lost will not be known accurately until withdrawal.

A possibility is the occurrence of a slow leak either through which oil can escape or be interchanged with water from a non-cavern source. Cavern salt creep would possibly prevent an oil pressure drop at the surface, thus pressure sensors would not detect a change. While the possibility is remote, the consequences could be dire. For example, the non-certified cavern #3 at Bryan Mound is suspected of having a fresh water source, i.e., a communication with the outside. Should this occur in one of the certified caverns the possibility would become a reality.

Techniques which would provide periodic accounting of the oil have been identified. These are:

1. In-situ measurements of the oil/brine level.

- 2. Periodic offsite withdrawal followed by refill.
- 3. Exchange of oil and brine with excess onsite storage.

In-situ measurements of the oil/brine interface can be performed by existing well logging services. Periodic measurements would confirm the **gross** quantity of oil available and would provide a reasonable check on serious cavern problems.

Periodic offsite withdrawal and refill cycles establish, with some accuracy, cavern losses due to roof problems. Several existing caverns may be damaged or become extremely limited in their future use due to the necessary use of raw water for withdrawal. Caverns in close proximity to other caverns (Cavern #15 at Bayou Choctaw, Cavern #2 at Bryan Mound, Cavern #9 at West Hackberry, etc.) cannot be cycled periodically. New expansion caverns are sufficiently close that excessive leaching cycles could endanger them or at least place them in a seriously questionable state.

Periodic exchange of oil and brine with excess **onsite** storage offers an accurate periodic accounting of the oil without damage to the caverns. However, such excess **onsite** storage does not currently exist nor is it planned. Excess storage would have to be leached during the leach/fill program and/or existing or planned cavern(s) dedicated as excess. This decision necessarily requires other inputs including costs, other beneficial factors, etc.

<u>Crude-oil stability</u> technical concerns have been discussed in a previous section. The long term monitoring program must provide the means of obtaining samples sufficient to ascertain the quality of crude oil. Since one potential problem is stratification, it is clear that samples must be obtained from various "levels" or heights. There are no known techniques for performing the chemical analysis insitu, therefore, physical samples must be extracted.

Currently , the internal cycling operation plans specify that samples from the oil will be withdrawn as it passes the metering station. The accessibility of the oil in this mode is limited to the surface tank storage volumes (800,000 B at Bryan Mound, for example) or unfilled volume(s), which will be nonexistent after fill.

Two other techniques of sampling are possible for the leached caverns:

- 1. In-situ sampling via a sampling probe, and
- 2. Sampling during total volume exchange with an excess cavern.

Sampling probes were used in Germany to sample their storage caverns. Their design dictates the use of slick holes (no brine string) thus requiring significant rig time to remove the brine string, multiple runs of the sampling probe, and brine string replacement.

Sampling during a total volume exchange requires excess volume to be available as previously discussed. It is clear that if there were dedicated excess volume and a total oil/brine interchange, that sampling via existing equipment would be rudimentary.

The choice of sampling technique is inherantly dependent on the availability of excess cavern storage and the economics of oil/brine interchange with sampling, etc. These tradeoffs are discussed below.

Cavern Integrity measurements are concerned with the structural integrity of the salt caverns and mine. To date, some surface' subsidence measurements have been made at Bayou Choctaw and others are planned. These will provide a baseline for future measurements. An ongoing program at the other sites should be established. Basically, surface subsidence measurements are economical, and could provide evidence of long-term settling and cavern problems. The quantity of points referenced in the Wong Associates [O-l] work at Bayou Choctaw may not be necessary but that level of detail can be ascertained later.

In-situ measurements of leached caverns are not deemed very useful in the long term. It is strongly recommended that a series of borehole deformation measurements (caliper logs) be made in the cavern wells following drilling and prior to commencing leaching operations. Anomalous closure rates in any boreholes will alert the project to unusual behavior thus possibly providing an early warning of serious problems.

In-situ and/or periodic measurements of casing corrosion are not technically feasible. Analysis of the environment and materials will provide an estimate of casing lifetimes. Alternate materials may be desired if the lifetimes estimates will materially affect the program.

Tradeoffs and Recommendations

It is recommended that a long-term monitoring plan be developed and initiated. The plan should detail measurements in the following areas:

- 1. Surface subsidence measurements.
- 2. Crude-oil sampling,
- 3. Borehole caliper logs, and
- 4. Cavern volume establishment (excess storage).

This plan may need to be supplemented by special studies where particular circumstances warrant, e.g., geological/site characterization measurements, geophone measurements, etc.

Inherent in the plan are tradeoffs between the cost of extensive measurements and/or capabilities and the usefulness of the data in safeguarding the SPR, These tradeoffs have not been analyzed here in sufficient detail or with sufficient knowledge of all program constraints to finalize a program. This overview does make recommendations including time schedules, however, which will provide a start,

Surface Subsidence Measurements

Surface surveys have been started and should be expanded. A reasonable approach would include surveys of a few points over all existing onsite caverns on a semiannual basis and over all new caverns on at least an annual basis. Any appreciable subsidence detected might dictate additional measurements. Measurements over the Weeks Island mine do not appear warranted.

Crude-Oil Sampling

The stability of the crude oils is of sufficient concern to dictate a fairly intensive initial effort. Pending the outcome of the early efforts, future sampling may be relaxed or intensified.

Estimated costs of sampling are \$15-20K per cavern for a sampling probe, or electrical pumping costs of \$45-60K for a transfer of oil between caverns (10 MMB assumed). A sampling probe thus appears more economical unless other considerations dictate an oil transfer. It is recommended that a single cavern of each oil category (sweet and sour) on each site be initially sampled (at multiple depths) on a three month interval following fill. This can be relaxed to a six month or greater interval after a year. All other caverns on each site should initially be sampled at least annually until sufficient confidence is established in the similar behavior (or disbehavior) of caverns on a given site. Samples should also be analyzed from Weeks Island on a three month interval initially, although the ability to sample various depths is limited.

Borehole Caliper Logs

Borehole caliper logs should be run an all new wells after drilling and again following leaching of the sump. This period of time should provide an early indication of possible anomalous regions in the dome.

Cavern Volume Establishment (Excess Storage)

Establishing excess storage **onsite** is costly but offers several advantages and is thus recommended. Advantages include:

- 1. Accurate accounting of the oil available for withdrawal from other caverns.
- 2. A storage for brine which can be used to prolong the life of endangered (coalesence) caverns,
- 3. An emergency storage area in the case of a catastrophic failure or pending failure of another cavern, and
- 4. A means of sampling all oil in a cavern during an oil transfer.

The extent of excess storage on sites and the location in the dome and within the piping complex are subject to further consideration. Table O-l lists one possible choice.

TABLE O-l

<u>Location</u>	<u>Size</u>	<u>Comments</u>
Bryan Mound	16 MMB	Suf f ic ient to totally exchange all except cavern #5 (31.8 MMB). Only the lower half of it could be emptied.
West Hackberry	12 MMB	All caverns could be exchanged.
Bayou Choctaw	8.1 or 15.7 MMB	Only four caverns are currently planned. 8.1 MME would empty all but the largest.
Sulphur Mines	11.7 or 5.4 MMB	Only three separate caverns are planned. The greatest uncertainty is in the largest cavern(s) (caverns #2, 3, and 5 have coalesced).
Weeks Island		No storage is practical

Location of the excess cavern(s) should be necessarily on a pipe line from the pumping station which is separate or does not contain the single largest or all of the equally largest caverns at the site. It would also be useful that it not be located on a line with any caverns which have a stability concern. This judicious location of storage maximizes its onsite utility.

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West Hackberry Complex: Cameron Parish, LA.
Bryan Mound Complex: Brazaria Co., TX.

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SPR General

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- 31. "Inspection Report SPR Site: Bryan Mound", Office of Inspector General, March 15-23, 1978.
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 Gas Industries, the Government and Others, May 5, 1955.
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- 35. "Security Implementation Guidelines St. James SPR", SAND 78-2106, Sandia Laboratories, Albuquerque, NM, December 13, 1978.
- 36. "Security Implementation Guidelines West Hackberry SPR", SAND 78-1042, Sandia Laboratories, Albuquerque, NM.
- 37. "Security Implementation Guidelines Weeks Island SPR", SAND 78-1381, Sandia Laboratories, Albuquerque, NM, August 15, 1978.

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- 40. "Bayou Choctaw", BC-Ol--00, Site Directive", April 18, 1978.
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- 3. "National Strategic Oil Storage Program, Phase 3, Underground Mined Storage Feasibility Analysis, Early Storage Program Sites", US Federal Energy Administration, Acres American, Inc., June 1976.
- 4. "Review of Applicable Technology Solution Mining of Caverns in Salt Domes to Serve as Repositiories for Radioactive Wastes", Fenix & Scisson, Inc., June 15, 1976.

An additional 80 Geotechnical References are located in an Annotated Bibliography, Appendix Q_{\bullet}

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- "SPR Texoma Group Salt Domes, Draft EIS Appendices A & B, West Hackberry Expansion, Black Bayou, Vinton, Big Hill", FEA/S-77/323, Federal Energy Administration, National Energy Information Center, September 1977.
- 3. "Final EIS, SPR Capline Group Salt Domes, Iberia, Napoleon-ville, Weeks Island Expansion, Bayou Choctaw Expansion, Chacahoula, Iberia Iberville, & Lafourche Parishes, LA", FEA-DES 77-9, US Department of Energy, July 1978.
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- 21. "U.S. DOE Monitoring Plan for Bryan Mound Brine Disposal to the Gulf of Mexico", November 22, 1978.
- 22. "Interagency Agreement Between the FEA (DOE) and the NOAA, and Amendments 1 through 4", dated January 13, 1978.

Appendix Q

Annotated Bibliography of Geological Documents Related

to the Strategic Petroleum Reserve Program

Q-1. Acres American, Inc., November, 1976, "Strategic Petroleum Reserve, Underground Mined Storage, Ironton Mine Geotechnical Study," 32 p.

The object of the study was to "confirm that" Ironton lime-stone mine at Ironton, Ohio is geotechnically suitable for the longterm storage of crude oil. To assess cavern stability and oil containment, the following tasks were performed: an in-mine survey, diamond core drilling from the surface, water pressure testing in the lower sections of boreholes, laboratory testing, and data analysis. It was concluded that from a technical standpoint the Ironton mine would be suitable for crude oil storage. The geology sections are basically derived from the in-mine survey and are site specific to the mine. The geological discussion is limited to the formation which contains the mine (Maxville formation), fractures and joints in the mine, and mine hydrogeology.

Q-2. Acres American, Inc. in association with RE/SPEC Inc., November, 1977, "U.S. Federal Energy Administratin National Strategic Oil Storage Program: Weeks Island Mine Geotechnical Study," Volume 1. Undertaken for Gulf Interstate Engineering Co. under contract FEA-1251-75, 61 p. plus figures and tables.

Volume 1 of the geotechnical report on Weeks Island Mine includes a history and geology of the Weeks Island dome, the field and laboratory investigation program, mine stability and containment, mine conversion, evaluation of safe web thickness, and monitoring and inspection sections. Al though the appendices (Volume 2) were not seen, there is a report included on the geology by Dr. D. H. Kupfer, as well as data supplied by Morton Salt Company, and the results of laboratory tests. The conclusion from Volume 1 is that this report does not appear to be as thorough geologically as the Golder Assoc. report on Cote Blanche and concentrates more on the engineering aspects of the problem.

Q-3. Testimony of Michael F. Carosella (DOE), Neal Van Fossan and Peter Kelsall (Gulf Interstate Engineering Company), and Ron Kear (Dames & Moore) before the State of Louisiana, Office of Conservation, August 16, 1978, Docket Number 505-78-4.

<u>Carosella</u> is Acting Director of the program planning division of the <u>SPR</u> program and came to provide technical information on the Weeks Island site. He made no comments on geology.

<u>Van Fossan</u> is vice president of Gulf Interstate. His testimony includes geologic evidence on weeks Island dome, a **cross**-section and structure contour map. He seems to have very specific geologic information but it is not presented with this report. At Weeks Island dome hydrocarbon prospecting began in 1905 with 282 wells drilled prior to 1978. The location of oil and gas wells are plotted on the structure contour map.

Kelsall is Supervising Engineer for Gulf Interstafe and describes the mine history, conversion for storage and operating method for SPR. He describes the geotechnical invest igation to confirm the suitability of the mine for storage, i.e., over a 40-50 year operating period the mine would remain stable and would retain crude oil. He refers to the Acres American, Inc., study and report by Dr. Donald Kupfer of LSU. Kelsall refers to "blowouts" in salt, shear zones in lower levels of the mine, slabbing or exfoliation of pillars, and salt creep. He states the latter two are not zones of structural weakness which will be detrimental to the stability of the cavern: and the former two will not occur at a significant rate.

 $\underline{\text{Kear}}$ is an associate of Dames & Moore; his testimony had no geolog ic significance .

Q-4. Dames & Moore, October 10, 1978, "Preliminary Draft, Napoleon-ville Dome Brine Injection Feasibility and Environmental Assessment Report."

The alternative methods of disposing of 1.9 billion barrels of brine from leaching which are considered are disposal in the Gulf of Mexico or at several candidate well fields around Napoleonville dome. Seismic data has been ordered to dete'rmine the existence of possible faults and no-flow boundaries in the aquifers. The drilling of a brine disposal test well is suggested to measure well and aquifer performance.

Q-5. Ecology and Environment, Inc., July 19, 1978," Feasibility and Terrestrial Environmental Assessment of Brine Disposal Via Subsurface Injection at the Bryan Mound SPR Site."

This report was the result of an EPA request for further information on deep well brine dispoal at Bryan Mound before taking action on a permit application to discharge the brine into the Gulf of Mexico. The discussion includes the geologic environment of the upper and lower disposal reservoirs, the groundwater resources, seismic and fracture risks, influence on adjacent oil and gas production; adjacent exploratory holes, well arrangement and vertical separation, injection pressure, potential constraints and limitations, hydraulic conclusions, a reservoir analysis, ISF/sonic logs of the pertinent disposal zones and core logs.

Q-6. Fenix & Scisson, Inc., May 1976, "Final Report, Project I, Investigation of New Leached Caverns in Salt Domes," Volumes I and II.

Project I is a prototype study of five primary sites and eight alternate sites for the storage of crude oil as part of the Strategic Petroleum Reserve program. For each of the 13 domes (Chacahoula dome, Allen dome, Black Bayou dome, Napoleon-ville dome, Eugene Island dome, White Castle dome, Iberia dome, Vinton dome, Nash dome, West Columbia dome, Damon Mound dome, Big Hill dome, San Luis Pass dome), facility identification, design, and cost studies were conducted. For each dome a 20 to 30 page geology section is presented which details physiography, regional geology, local geology, salt dome configuration, gas and oil production, leaching water supply, brine disposal, floods, wind, seismic risk, mineral ownership, and exploration required. Geologic cross-sect ions, structure contour maps (1000 ft. contour interval) and seismic risk maps are provided.

Q-7. Fenix & Scisson, May, 1976, "Final Report, Project II, Engineering Feasibility Study of Underground Storage in Existing Leached Caverns in Salt Formations."

In this study, data on the feasibility of storing crude oil in salt domes were collected and analysed for the Early Storage Program, and three primary sites were selected (West Hackberry, Bayou Choctaw, and Bryan Mound). The present report is a detailed technical, environmental, and cost analysis for West Hackberry, Eayou Choctaw, and Sulphur Mines (an optional site) salt domes. The study of the Bryan Mound site was assigned to the Dallas office of the FEA. For each of the three sites, the geologic considerations (regional, local, caprock, salt, oil and gas production, present storage, flood, wind and seismic risk, exploration required) are discussed. Geologic cross-sections, structure contour maps and seismic risk maps are included.

Q-8. Golder Associates, October, 1977, "Report to Gulf Interstate Engineer ing Co. on Geotechnical Study of Cote Blanche Island Salt Mine, New Iberia, Louisiana," Volume I, Text and Figs, 161 p.

The study of Cote Blanche Island Salt mine was made to determine the suitability of the existing mine to store crude oil as part of the SPR program and to assess geotechnical problems which might arise in relocating the existing mine above the oil storage cavern. Descriptions of the regional and site geology, the features mapped during the field investigation program, an assessment of the stability of the mine and the containment properties of the salt are included. Much of the geology is based on a report prepared by Dr. D. H. Kupfer which appears in the Apendix (Volume II). In Volume I, a compilation of existing data

as well as new data gathered for this study is presented and appears thorough. The data is well documented and many references are pertinent to SPR and should be collected/examined. There are also many geologically pertinent figures and tables here.

Q-9. Golder Associates, October, 1977, "Report to Gulf Interstate Engineering Co. on Geotechnical Study of Cote Blanche Island Salt Mine, New Iberia, Louisiana," Volume II, appendices.

The appendices to the Cote Blanche Island salt mine geotechnical study include the following geological sect ions: Append ix II - Geological report prepared by Dr. D. H. Kupf er (61 p. plus supplement). The report appears extremely detailed and thorough and contains an annotated bibliography; Appendix III - Oil exploration holes drilled through salt dome; Appendix IV - Logs for selected drill holes: Appendix V - Directional surveys for selected drill holes; Appendix VI - Results of salt quality analyses; Appendix VIII - Petrographic and spectrographic test results: Appendix VIII - Drill hole logs; Appendices IX - Results of chemcial tests on samples from "Yellow" salt zone: Appendix X - Strength test results; Append ix XI - Longitudinal and shear wave velocities; Append ix XI I - In-situ tests to determine containment properties of salt: Appendix XIII - Reconnaissance investigation of shafts; Appendix XIV - Laboratory permeability results; Appendix XV - Chemical analysis of water samples from Cote Blanche mine.

Q-10. Golder Associates, December 1978, "Draft Report on Discussions Held in New Orleans on November 29 and December 1, 1978, Concerning Potential Problems with Underground Oil Storage Caverns in Salt Domes," Volume I, Summary volume, 13 p.

It was proposed to reduce the pressure on the oil stored in caverns so that zero net pressure is attained at the surface. The aim of the meeting was to investigate adverse effects associated with depressurization, i.e., excessive closure of the cavern: structural instability of the roof, walls, or floor; damage to access holes and pumping equipment, surface subsidence: and loss or contamination of stored fluid. Methods suggested to assess cavern stability and depressurization effects include field measurements and tests as well as laboratory and numerical modelling. Suggested field measurements to monitor cavern stability were: 1) measurement of surface displacement, 2) sonar measurements, 3) pressure and volume measurements of fluids entering and leaving cavern, 4) borehole logs, 5) microseismic monitoring, 6) downhole deformation monitoring devices, 7) other downhole devices, 8) acoustic monitoring, 9) stress measurements, 10) cavern hydrodynamic studies. Site specific recommendations were made for West Hackberry Cavern Number 6, Bayou Choctaw Caverns Number 15 and 17, Bryan Mound Caverns Number 4 and 5, and Bryan Mound Cavern Number 2.

Q-11. Golder Associates, December, 1978, "Draft Report on Discussions Held in New Orleans on November 29, and December 1, 1978, Concerning Potential Problems with Underground Oil Storage Caverns in Salt Domes," Volume II, Main Text and Figures, 34 p.

This report is somewhat more detailed than Volume I (Summary) and has more specific site recommendations.

Q-12. Gulf Coast Association of Geological Societies and the American Association of Petroleum Geologists, 1972, "Tectonic Map of Gulf Coast Region, U.S.A."

The tectonic map is at a scale of 1:1,000,000 and has major faults, folds, salt diapirs and structure contours plotted.

Q-13. Gulf Interstate Engineering Company, November 8, 1977, "Solution Cavern Certificates of Usability and Integrity for the Strategic Petroleum Reserve Program of the Department of Energy, West Hackberry Site," (Book 2 of 2).

This report includes a certificate of cavern usability and integrity and a certificate of authority, guestions to be resolved, results of tests, surveys, and remedial works, a summary of investigations and test results on cavery #9, cavern #9 statistics, and operating limitations. The supporting documentation on cavern #9 presented as exhibits are the casing and cavern test programs, cement bond logs, pressure recorder chart, certificate of calibration, sonar caliper brochure, sonar caliper survey, gyro azimuth and deviation survey, graphic representation of separation of cavern #8 and #9, casing cal iper survey, and hydraulic calculations.

Q-14. Gulf Interstate Engineering Company, March 27, 1978, "Solution Cavern Certificates of Usability and Integrity for the Strategic Petroleum Reserve Program of the Department of Energy, Bayou Choctaw Site."

This report includes certificates of cavern usability and integrity and a certificate of authority, a summary of investigations and test results of cavern #20. The supporting documentation on cavern #20 presented as exhibits are the casing and cavern test program, cement bond log, pressure recorder charts, certificate of calibration, sonar brochure, sonar calipher survey, gyro azimuth and deviation survey, casing caliper survey, temperature survey, hydraulic calculations, and miscellaneous drawings.

Q-15. Gulf Interstate Engineering Company, May 1978, "As-Built Drawings for Bayou Choctaw Complex, Bryon Mound Complex, West Hackberry Complex, Surphur Mines Complex."

The drawings show depth to the top of caprock and the top of salt, and construction details for wells at Bryan Mound, West Hackberry, Sulphur Mines, and Bayou Choctaw. Construction drawings of these wells are included: Bryan Mound - well in complex cavern #1, storage wells in #2, 4, 5; West Hackberry - storage well in #6, reentry well in #6B, well in #7, 8, 9 storage well #11, disposal wells #1, 2; Sulphur Mines - well in #2, 4, 5, 6X, 6Y, 7A, 7B, disposal well #1; Bayou Choctaw - well in #1, 2, 3, 8A, 11, 13, 18, 19, 20, disposal well #1.

Q-16. Gulf Interstate Engineering Company, May 8, 1978, "Solution Cavern Certificates of Usability and Integrity for the Strategic Petroleum Reserve Program of the Department of Energy, Bryan Mound Site."

This report includes a certificate of cavern usability and integrity and a certificate of authority, a summary of investigations and test results in cavern #1, and statistics on cavern #5. The supporting documentat ion of cavern #5 presented as exhibits are the casing and cavern test program, cement bond log, pressure recorder chart, certificate of calibration, sonar brochure, sonar caliper survey, gyro azimuth and deviation survey, casing and caliper survey, temperature survey, hydraulic calculations, and miscellaneous drawings. A copy of this report with the same title in DOE New Orleans office is on #1B alone and has #1B supporting documentat ion same as descr ibed for #5 above.

Q-17. Jirik, C. J., and Weaver, L. K., 1976, "A Survey of Salt Deposits and Salt Caverns, Their Relevance to the Strategic Petroleum Reserve," Federal Energy Administration Report FEA/S-76/310, 64 p.

Bedded salt and salt domes in the U.S. are discussed in terms of their potential for the storage of petroleum. Salient statistics are presented on on- and offshore salt domes in Texas, Louisiana, Alabama, and Mississippi. Since the 1940's, underground caverns have been used for storing liquif jed petroleum gases (LPG) and natural gas. Information on the LPG storage operations is summarized in tables. In 1975, there was potential space available for the storage of 304,667,000 barrels of hydrocarbons in salt strata, salt domes, mines, and other reservoirs in 28 states; 93 percent of the storage capacity was in salt.

Q-18. Law Engineering Testing Company, July 15, 1977, "Report of Geotechnical Investigation, Bryan Mound Storage Site, Freeport, Texas.

The purpose of this geotechnical investigation was to determine the **stratigraphy of** the subsurface materials at the site and to obtain data and information about the general character and properties of the subsurface materials to permit evaluation of foundation types and capacities for the proposed construction. This is basically a report on the suitability of soils to support facility foundations.

Q-.9. Louis Records and Associates, Inc., October 1978, "Well History, Brine Disposal Well X4, Bayou Choctaw, Iberville Parish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, sidewall core analysis, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Conservation Dept. documents, location plat, and well logs (borehole geometry, gamma/cement bond, caliper, induction electrical, ISF/sonic, continuous directional).

Q-20. Louis Records and Associates, Inc., November 1978, "Well History, Brine Disposal Well #7, Bayou Choctaw, Iberville Parish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, sidewall core analysis, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Conservation Dept. documents, locat ion plat, and well logs (caliper, gamma/cement bond, horehole geometry, compensated neutron density, induction electrical).

Q-21. Louis Records and Associates, Inc., November 15, 1978, "Well History, Brine Disposal Well #8, Bayou Choctaw, Iber-ville Parish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log 1 ist ing, cement slurry properties, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Conservation Dept. documents, location plat, and well logs (caliper, induction electrical, borehole geometry, continuous directional, ISF/sonic).

Q-22. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal Well #10, Bayou Choctaw Site, Calcasieu Parish, Louisiana."

The report includes a narrative history, well and well-head schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (borehole geometry, compensated neutron density, ISF/sonic, continuous directional, continuous dipmeter, caliper, cement bond, Cyberlook, SARABAND).

Q-23. Louis Records and Associates, Inc., November 1978, "Well History, Brine Disposal Well #11, Bayou Choctaw, Iberville Parish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Conservation Dept. documents, location plat, and well logs (caliper, borehole geometry, cement bond, induction electrical, laterolog).

Q-24. Louis Records and Associates, Inc., December 28, 1978, "Tabular Listing of SARABAND, a Sandstone Analysis for Brine Disposal Well **\$12**, Bayou Choctaw," with SARABAND Log and Induction, Neutron Density, and Sonic Logs.

SARABAND (a Schlumberger computer processed log using induction, neutron, density, and sonic logs) is included in graphic and tabular form. The tabular printout is for depths between 5952.0 and 7938.0 ft and includes permeability, porosity, water saturation, hydrocarbon density, clay volume, cumulative porosity, and cumulative hydrocarbons in depth increments of one ft. The individual logs are also included,

Q-25. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal Well X18, Bayou Choctaw Site, Calcasieu Parish, Louisiana."

The report includes a narrative history, well and well-heat schematics, depth vs. days history, chronological log listing, casing report, and well logs (borehole geometry, differential temperature, acoustic cement evaluation).

Q-26. Louis Records and Associates, Inc., No Date, "Well History, Re-Entry Well No. 19A, Bayou Choctaw Site, Calcasieu Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, locat ion plat, and well logs (caliper, compensated density, induct ion elec trical, gamma/cement bond).

Q-. 7. Louis Records and Associates, Inc., No Date, "Well History, Work-Over Well No. 20, Bayou-Choctaw Site, Calcasieu Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, chronological log listing, casing report, and caliper log.

Q-28. Louis Records and Associates, Inc., January 3, 1979, "Operations Manual, Bryan Mound Disposal Wells."

Information is provided for brine disposal wells #1, 1A, 2A, 2B, and 3A and includes well, wellhead, and gravel pack schematics, location plat, and injection zone section of ISF/sonic log.

Q-29 Louis Records and Associates, Inc., November 1978, "Work-over Summary, Cavern Well #1, Bryan Mound, Brazoria County, Texas."

The report includes a narrative history, well and wellhead schematics chronological log listing, cement slurry properties, casing and tubing report, Texas RR Commission documents, cement bond log and electromagnetic thickness tool log.

Q-30. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal Well No. 1A, Bryan Mound Site, Bryan Mound, Texas."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Texas RR Commission documents, location plat and well logs (caliper, cement bond, ISF/sonic, compensated neutron density, continuous dipmeter, acoustic cement evaluation).

Q-31. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal, Well 2A, Bryan Mound Site, Bryan Mound, Texas."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry proper ties, core analysis, drilling fluid summary, casing report, Texas RR Commission documents, location plat, and well logs (ISF/sonic compensate neutron density, perforated depth control, cement bond, caliper, borehole geometry, continuous dipmeter, acoustic cement evaluation).

Q-32. Louis Records and Associates, Inc., December 1978, "Well History, Br ine Disposal, Well #2B, Bryan Mound, Brazor ia Country, Texas."

The report includes a narrative history, well, wellhead, and gravel schematics, depth vs. days history, directional deviation surveys, chronological log listing, cement slurry properties, drilling fluid summary, casing and tubing report, Texas RR Commission documents, location plat, and geophysical logs (ISF/sonic, caliper, cement bond, continuous dipmeter, compensated neutron density, microelectrical, induct ion elec tr ical, acoustic cement bond).

Q-33 Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal, Well No. 3A, 'Bryan Mound Site, Bryan Mound, Texas."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Texas RR Commission documents, location plat, and. well logs (caliper, borehole geometry, compensated neutron density, ISF/sonic, perforated depth control, acoustic cement evaluation, continuous dipmeter, SARABAND).

Q-34 Louis Records and Associates, Inc., October 1978, "Well History, Brine Disposal Well #3B, Bryan Mound, Brazoria County, Texas."

The report includes a narrative history, well, wellhead and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, sidewall core analysis, drilling fluid summary, casing and tubing report, water analysis, Texas RR Commission documents, location plat, and well logs (cement bond, caliper, compensated neutron density, continuous directional, ISF/sonic, continuous dipmeter).

Q-35. Louis Records and Associates, Inc., January 1979, "Work-over Well History, Brine Disposal Well #1, West Hackberry, Cameron Parish, Louisiana."

The report includes a narrative history, well, wellhead and gravel packs schematics, completion report, previous well schematic, electric log section, chronological log listing, tubular report, comprehensive water analysis, Louisiana Dept. of Conservation documents, gamma log.

Q-36. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal Well No, 1A, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs, days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (ISF/sonic, borehole geometry, compensated neutron density, continuous directional, continuous dipmeter, acoustic cement evaluation).

Q-37. Louis Records and Associates, Inc., No Date, "Well History, Brine Disposal Well 1C, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (gamma, cement bond, borehole geometry, compensated neutron density, ISF/sonic, cement bond/gamma, continuous directional, SARABAND).

Q-38. Louis Records and Associates, Inc., No Date, "Well History, West Hackberry Field, Brine Disposal Well No. 2A."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (compensated neutron density, ISF/sonic, borehole geometry, acoustic cement evaluation, continuous dipmeter, cont inuous direct ional, SARABAND).

Q-39. Louis Records and Associates, Inc., December 1978, "Well History, Brine Disposal Well #28, West Hackberry, Cameron Par ish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing! cement slurry properties, sidewall core analysis, dr ill ing fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Dept. of Conservation documents, location plat, and well logs (caliper, induction electrical gamma, cement bond, continuous directional).

Q-40. Louis Records and Associates, Inc., No Date, "Well History, West Hackberry Field, Bc ine Disposal Well No, 2C."

The report includes a narrative history, well and wellhead schematics, depth vs. days histocy, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (compensated neutron density, ISF/sonic, borehole geometry, acoustic cement evaluation, acoustic cement bond/ggmma, continuous directional),

Q-41. Louis Records and Aasooiates, Inc., December 1978, "Well History, Brine Disposal Well #2D, West Hackberry, Cameron Far ish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, sidewall core analysis, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Dept. of Consecvat ion documents, location plat, and well logs (caliper, bocehole geometry, cement bond, gamma, compensated neutron density, induction electrolog, directional survey, continuous directional).

Q-42. Louis Reeocds and Associates, Inc., December 1978, "Well History, Brine Disposal Well #2E, West Hackberry, Cameron Parish, Louisiana."

The report includes a narrative history, well, wellhead, and gravel pack schematics, depth vs, days history, directional deviation survey, chronological log listing, cement slurry proper ties, sidewall core analysis, drilling fluid summary, casing and tubing report, comprehensive water analysis, Louisiana Dept. of Conservation documents, location plat, well logs (cal ipec, cement bond, induct ion electcolog, bocehole geometry, continuous directional).

Q-43. Louis Records and Associates, Inc., No Date, "Well History, Workover Well No. 6B, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, directional deviation survey, chronological log listing, drilling fluid summary, casing report, location plat, and well logs (perforating and collar, acoustic cement evaluation).

Q-44. Louis Records and Associates, Inc., No Date, "Well History, Re-Entry Well No. 6C, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (borehole geometry, cement bond, continuous directional, induction spherically focused).

Q-45. Louis Records and Associates, Inc., No Date, "Well History Workover Well No. 7, West Hackberry Field, Cameron Parish, Louis iana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, chronological log listing, cement slurry properties, casing report, and well logs (caliper, acoustic cement evaluation).

Q-46. Louis Records and Associates, Inc., No Date, "Well History Re-Entry Well No. 7A, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, direct ional deviat ion survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (borehole geometry, acoustic cement evaluation, continuous directional, induction spherically focused).

Q-47. Louis Records and Associates, Inc., No Date, "Well History, Re-Entry Well No, 78, West Hackberry Field, Cameron Par ish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report,

Louisiana Conservation Dept. documents, location plat, and well lags (acoustic cement evaluation, continuous directional, induction spherically focused).

Q-48. Louis Records and Associates, Inc., No Date, "Well History, Re-Entry Well 8A, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat and well logs (ISF/sonic, compensated formation density, borehole geometry, caliper, continuous directional, acoustic cement evaluation).

Q-49. Louis Records and Associates, Inc., No Date, "Well History, Re-Entry Well No. 8B, West Hackberry Field, Cameron Parish, Louisiana,"

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (acoustic cement evaluation, borehole geometry, continuous direction, ISF/sonic).

Q-50. Louis Records and Associates, Inc., No Date, "Well History, Work-Over Well No. 9, West Hackberry Field, Cameron Parish, Louisiana,"

The report includes a narrative history, well and wellhead schematics, depth vs. days history, chronological log 1 ist ing, cement slurry properties, casing report, and well logs (borehole geometry, acoustic cement evaluation).

Q-51, Louis Records and Associates, Inc., No Date, "Well History Re-Entry Well No. 9A, West Hackberry Field, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, and well logs (acoustic cement evaluation, caliper, compensated formation density, continuous directional, induction sper ically focused).

Q-52. Louis Records and Associates, Inc., No Date, "Well History Re-Entry Well No, 9B, West Hackberry Field, Cameron Parish, Louisiana." The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, core analysis, drilling fluid summary, casing report, Louisiana Conservation Dept. documents, location plat, well logs (acoustic cement evaluation, caliper, compensated formation density, continuous directional, ISF/sonic).

Q-53. Louis Records and Associates, Inc. December, 1978, "Well History, Re-Entry Well #11A, West Hackberry, Cameron Parish, Louisiana."

The report includes a narrative history, well and wellhead schematics, depth vs. days history, directional deviation survey, chronological log listing, cement slurry properties, drilling fluid summary, casing and tubing report, Louisiana Dept. of Conservation Documents, location plat, well logs (cement bond, caliper, directional survey, induction electrolog, computed diplog).

Q-54. Magorian, T. R., November, 1978, "Geotechnical Study, Bayou Choctaw, Brine Disposal Reservoir Analysis (proposed expansion)," Consultant's report to U.S. Dept. of Energy, Strategic Petroleum Reserve Program.

In this report, sands with maximum brine injectivity rate and volume were identified from geophysical data and reservoir analysis to be located near the base of the Miocene section. Sand catalogs for each storage site were prepared and are included: faults which may affect disposal operations are shown on accompanying maps (1" = 2000'). Additional disposal wells are recommended, and deep drilling is suggested below 7000 ft to test the massive Miocene sands.

Q-55. Magorian, T. R., November, 1978, "Geotechnical Study, Bryan Mound, Brine disposal Reservoir Analysis (Containment)," Consultant's report to U.S. Dept. of Energy, Strategic Petroleum Reserve Program.

In this report, sands with maximum brine injectivity rate and volume were identified from geophysical data and reservoir analysis to be located near the base of the Miocene section. Sand catalogs for each storage site were prepared and are included: faults which may affect disposal operations are shown on accompanying maps (1" = 2000'). The possibility of leakage upward through faults from the Bryan Mound #1 disposal well was investigated.

Q-56. Mahtab, M. A., Lamb, D. W., Van Sambeek, L. L., and Gill, S. D., 1978, "National Strategic Crude Oil Storage in Weeks Island Dome Salt Mine: I. Geotechnical Evaluation", Amer. Soc. Mech. Engr. 78-Pet-75.

Geologic features which were examined at the Weeks Island mine of interest to the SPR program were 1) zones of vertical banding and folding, 2) **shear zones**, 3) blowouts. The salt tested impermeable; brine, oil, and gas leaks are thought to be only local, The pillars exhibited varying degrees of spalling, and the roof showed no signs of stress or failure. The facility was therefore certified as suitable for crude oil storage.

Q-57. Parsons-Gilbane, 1978, "Activities of the Technical Committee, Strategic Petroleum Reserve Program, February-1978, November, 1978," Job No. 5822-1011.

This document contains the following reports: TR-l-Weeks Island Mine Rehabilitation; TR-2-Bayou Choctaw Rrine Disposal by Deviated Drilling: TR-3-Weeks Island Service Shaft Pipe Installation; TR-4-Overv iaw-Explosion Hazard Control, SPR Program; TR-5-Brine Disposal, Overview and Analysis, Interim Reports #1, 2, and 3; TR-B-Weeks Island Mine, Flofable Trash: TR-7-Inerting Weeks Island Atmosphere; TR-8-Weeks Tsland Cost Reduction Team; and 13 progress reports.

G-58. Parsons-Gilbane, August 15, 1978, "Brine Disposal, Analysis and Overview, Technical Committee, Strategic Petroleum Reserve."

The report looks at brine disposal options for the Bryan Mound, Bayou Choctaw, and West Hackberry sites because of previous unsatisfactory brine injection rates experienced in the SPR program. Pretreatment methods of the brine are considered such as the removal of suspended solids, oxygen, and iron and PH control. The nature of the problems encountered with disposal wells at the three SPR sites were attributed to self imposed and start-up problems, improper complet ion procedures, and incorrect downwell design.

Q-59. Parsons-Gilbane, August 30, 1978, "Brine Disposal, Analysis and Overv iew, Interim Report 2, Technical Committee, Strategic Petroleum Reserve."

The report contains the minutes from the technical meeting held August 23 and 24, 1978 and **a** list of recommendations drawn up at the meeting. A brine disposal monitor is suggested for each site. A change in brine pond design is recommended for Eayou Choctaw as pretreatment for the high solid content. Short term improvements in disposal operations at Bryan Mound are suggested such as the cleaning of the brine surge/storage pond to prevent sediment from clogging injection formations and procedures to prevent barium sulfate precipitation. Good injection rates at West Rackberry should be attained if correct brine handling and disposal procedures are adhered to. Chemical analyses of brine samples from Bryan Mound and Bayou Choctaw are included in the appendices.

Q-60. Parsons-Gilbane, October 10, 1978, "Brine Disposal, Analysis and Overview, Intermin Report 3, Technical Committee, Strategic Petroleum Reserve."

The report contains the minutes from the September 12 and 13, 1978, technical meeting. Procedures for upgrading inject ion well capacity are listed, the brine disposal activities at Bryan Mound, Bayou Choctaw, and West Hackberry are reviewed and guidelines for later disposal systems are considered. A study by N. W. Snyder on the solubility of calcium sulfate in brine and a discussion of onsite sampling and water quality at Bayou Choctaw by B, I. Loran is included. Br ine disposal status reports, chemical analyses of brines, and drawings for upgrading the brine pond at Sulphur Mines are in the append ices.

Q-61. PB/KBB, January, 1978, "Strategic Petroleum Reserve Facility, Bryan Mound, Texas, Supplemental Geotechnical Report."

This supplemental report was necessitated by alterations in the design and a few information gaps in the original geotechemical report by Law Engineer ing. Law Engineer ing Testing Company was contracted as part of the present study to drill two borings and perform laboratory tests to provide design recommendations for two relocated storage tanks. In-situ seismic tests were also performed in order to determine the shear modulus of the soil for the design of pump foundations. The appendix contains the boring plan, Atterbery limit test summary, consolidation test results, letter from Law Engineering and an analysis from M. T. Davisson, foundation engineer.

Q-62. PB/KBB, August 21, 1978, "Strategic Petroleum Reserve Program, Salt Dome Study, Sulphur Mines, Louisiana," PMTPO 1024.

Recommendations are made for the use of each of the caverns in the Sulphur Mines dome for crude oil storage. These items were considered in the assessment: cavern stability, cont inued brining, cavern coalescence, cavern shape, crude-oil cycling, cavern proximity to edge of dome and adjacent caverns. The geological section is very general with little site specific information. Dome cross sections show the top of the caprock and salt but give no information on surrounding sediments. In the drilling evaluation it is stated that voids produced by sulphur mining operations and associated rock falls and subsidence have resulted in loss of circulation during drill ing.

Q-63. PB/KBB with Louis Records and Associates, Inc., August, 1978, Final Report, Salt Dome Geology and Cavern Stability Analysis, Bayou Choctaw, Louisiana," (appendix annotated separately) PMTPO#919.

The project included the review of existing geologic studies, geologic field investigations (including drilling and coring), and laboratory testing of rock cores. The caprock was found to be composed primarily of gypsum, highly weathered and with closely spaced joints. A cavity was found at the caprock salt interface in one core hole, and two cavities were found in the upper 100 ft of the salt in the other corehole, causing drilling problems related to lost circulation. Gas and small amounts of oil were also encountered in drilling. Recommendations for cavern utilization are presented. Basic data for Bayou Choctaw presented in the report are: salt ultrasonic velocities (core 1), salt moisture contents and bulk densities (core 1), salt strength and elastic properties (core I and 2), caprock moisture contents and bulk densities (cores 1 and 2); initial elevations of subsidence manuments; cavern and brine well summary including date drilled, depth of well, depth of tap of cavern, gross volume, present status and remarks; structure contour map (1000' contour interval). Nine geologic cross sections (define salt and caprock limits but no information on surrounding sediments or structure: also define caverns with date of sonar survey given); log of core hole no. 1 including drilling operations log, geological log, S. P., caliper, conductivity, resistivity, gamma, potential, velocity, neutron logs: log of core hole no. 2 including potential, resistivity, velocity, gamma, neutron logs; location plat for subsidence movements with topographic contours drawn on a one Et contour interval.

Q-64. **PB/KBB** with Louis Records and **Associates**, Inc., August, 1978, "Append ix to Final Report, Salt Rome Geology and Cavern Stability Analysis, Bayou Choctaw, Louisiana." PMTPO #919

A field survey was made to assess the presence or absence of a major depression of approximately 300 meters amplitude in the salt surface at Bayou Choctaw dome. Models developed postulate thickening or thinning of the caprock and each give plausible results. The conclusion reached is that the anomaly results from caprock properties and not a depression. Tests conducted and reports included are as follows: microgravity survey (Weston Geophysical Corp.); report on laboratory testing of the physical properties of the salt and caprock drill core (Dames & Moore); geologic description and interpretation of field and rock core studies (Alfred J. Hendron, Jr., Geotechnical Engineer); mineralogical examination of caprock cores (R. E. Ferrell, Jr., Consulting Geologist): structure of the west flank (R. L. Thorns, Consulting Engineer); anhydritecrude oil correlation (Carbon Systems, Inc.); numerical analyses of Bayou Choctaw salt dome and cavern No, 4 (R, L. Thorns and R. M. Gehle); and elastic and time dependent finite element analyses of DOE-SPR caverns at Bayou Choctaw (J. Ghaboussi, A. J. Hendron, Jr., and R. Ranken).

Q-65. PB/KBB, September 6, 1978, "Strategic Petroleum Reserve Program, SPR Conceptual Design, Supplement to Salt Dome Geology and Cavern Stability Analysis, Bayou Choctaw, Louisiana." LTC #98

This is an engineering report and contains no geological data.

Q-66. PB/KBB, January 25, 1979, "Strategic Petroleum Reserve Program, Cavern #3, Investigation, Scope of Work, Bryan Mound, Texas," LTC #396

Fluid levels in cavern #3 fluctuate as much as 450 ft leading to the conclusion that there is a significant exchange of fluid with the surrounding aquifers. The scope of work outlined is for cavern logging and sampling, monitoring of fluid level and properties, and study of the sonar survey. Maps included here are cavern #3 contour maps (10 ft contour interval plus one 5 ft interval), a Freeport Sulphur Company map updated to 1935 (1" = 200") with depths of wells and depths to top of salt shown.

Q-67. Science Applications, Inc., July 25, 1977, "Assessment of the Impact of the Use of Shallow Aquifers for Brine Disposal at Bayou Choctaw," SAI-78-642-HU.

A comparison was made of the environmental risks associated with the use of shallow (2000-3000') salt water aquifers and deep (6000') aquifers for brine disposal at Bayou Choctaw. The potential problems are aquifer fracturing from excessive injection pressure, leakage through other operational or abandoned wells, and interference with nearby oil and gas operations. The study shows that both deep and shallow aquifers are acceptable. The shallower ones are more attractive for injection, but a monitoring system is essential to safeguard Baton Rouge's fresh water aquifers. The extent of the shallow aquifers are shown on maps as are, the major faults in the area. The study was prepared by Charles T. Smith and William J. Bernard of LSU as consultants to SAI. The list of references is also pertinent to site hydrology.

Q-68. Science Applications, Inc., October 28, 1977, "Site Environmental Action Report, Bayou Choctaw."

Geological and hydrological impacts specified are channel erosion due to increased barge traffic in Bull Bay, possible surface subsidence over storage caverns, possible fracture of the aquiclude above and below the disposal aquifer due to high brine injection pressures, cavity collapse between caverns 15 and 17, blowouts from the 19 abandoned wells if they are unplugged or improperly plugged, and oil spills, The geological and hydrological sections combined are about two pages long in this report (p. B-33, 37-38).

Q-69. Serata, S. 1978, "Geomechanical Basis for Design of Underground Salt Cavities", Amer. Assoc. Mech. Engr. 78-Pet-59, 43p.

Three basic geomechanical problems must be solved in designing salt caverns for the storage of crude oil: 1) numerical representation of the brittle-ductile properties of rock salt, 2) computer simulation of long-term behavior of salt cavities, and 3) verification of the model. These problems have been approached by defining the material properties of rock salt and developing the **rheological** finite-element (REM) computer simulation method. The salt cavity design for **LOOP** is used in the model.

Q-70. Sonic logs for brine disposal wells no. 1, 1-A, 1-C, 2, 2-C, 2-D, and 2-E, West Hackberry, and 2-A, East Mackberry.

The sonic logs are correlated on a large chart with potential brine disposal horizons marked in blue and actual brine disposal horizons marked in green.

Q-71. Sonic logs for brine disposal wells no. 1, 2, 3, 4, 6, 7, 10, Bayou Choctaw.

The sonic logs are correlated on a large chart with possible brine disposal horizons indicated in red.

Q-72, U.S. Department of Energy, December, 1977, "Strategic Petroleum Reserve, Final Env ironmen tal Impact Statement (Final Supplement to FEA FES 76/77-6), Bryan Mound Salt Dome, Brazoria County, Texas." DOE/EIS-0001.

This final supplement to the Bryan Mound final Environmental Impact Statement addresses the brine injection well system and the water intake system. The geological discussion is not detailed: it includes the chemical composition of the brine, the soils, Brazos River hydrological data (sediment analyses and water quality), impacts of construction and operation of injection and intake on the geology. Many of the conclusions dealing with the impacts of injection are neither supported nor referenced.

Q-73. U.S. Federal Energy Administration, January, 1977, Strategic Petroleum Reserve, Final Environmental Impact Statement for Cote Blanche Mine," FEA/S-77/016, FES 76/77-7.

The EIS contains a good regional characterization of the geology (16 pages) -and hydrology and sedimentation (45 pages) of the Cote Blanche mine. The information is summarized from previous reports and is well referenced, but is large scale and there is little if any data site specific to the mine. The impacts of geology, mineral resources, and hydrology are virtually dismissed with almost no supporting evidence.

Q-74. U.S. Federal Energy Administration, January, 1977, "Strategic Petroleum Reserve, Final Environmental Impact Statement, West Hackberry Salt Dome," FEA/S-76/503, FES 76/77-4

The geology section is brief and summarized from pervious reports. A structure contour map (100 ft contour interval) drawn on the top of the caprock, and an isopac map drawn on the thickness of the caprock are included but no control points are plotted. There are two geologic cross-sections and a structure map of the dome showing the location of oil and gas wells. The two geologic impacts addressed are channel erosion due to increased barge traffic in the Alkali Ditch and cavern collapse and subs idence. The only hydrologic impacts considered are on water quality.

Q-75. U.S. Federal Energy Administration (?), May 14, 1976, "Draft of Engineering and Cost Study of the Bryan Mound Storage Complex, Brazor ia County, Texas."

The geology test of this report is less than one page long. The structure contour map on the top of the salt is drawn on a 50 ft contour interval.

Q-76. U.S. Federal Energy Administration, 1977 (?), "Site Selection Decision Paper, Bryan Mound."

The question posed is whether Bryan Mound is suitable for the Early Storage Reserve program (ESR). The report contains no basic geologic data and provides just a brief summary of the geology (p. 4-5; appendix A, p. I). The main geological concern is that the dome is **structually** sound to prevent the loss of oil; structurally soundness is concluded without references or supporting **data** in the report. There are indications that there would be a high risk of cavern casing problems because of hot sulfur water in the **caprock**. The report states that in general **caprock** faulting is associated with piercement-type salt domes but "these faults have no effect on the storage characteristics of the dome since salt behaves as a plastic material" and heals. Nothing specific to Bryan Mound is stated about faulting. The environmental risks (p. 8-9) associated with disposing of brine in wells are discussed. The major risks mentioned are aquifer fracture, the possibility of fresh water contamination, and interference with oil and gas production.

Q-77. U.S. Federal Energy Administration, January, 1977, "Strategic Petroleum Reserve, Final Environmental Impact Statement", Bryan Mound Salt Dome, FEA/S-76/502, FES 76/77-6.

The report contains a generalized section on geology (4 pages) and also some ground water information (6 pages). Possible subsidence was the only geologic impact mentioned as being significant, (2 pages: Appendix I). It is stated here that brine discharged from the cavities would be used by Dow Chemical.

Q-78. U.S. Federal Energy Administration, August, 1977, "Strategic Petroleum Reserve, Supplement to Final Environmental Impact Statements for Weeks Island/Cote Blanche Mines," FEA/S-77/228, Supplement to FES-76/77-7 and FES 76/77-8.

This supplement is concerned with the construction and operation of the revised oil distribution system. The geological section is minor, and no basic geological data is presented. In the report the reader is referred to FES-76/77-7 and FES 76-77-8,

Q-79. U.S. General Accounting Office, August 14, 1979, "Report to the Congress of the United States, Questionable Suitability of Certain Salt Caverns and Mines for the Strategic Petroleum Reserve,*' EMD-7865.

'GAO says that SPR time constraints and the technical nature of the program have resulted in an inadequate analysis of risks. The report emphasises safety factors and sites the Mining, Safety, and Health Administration (MSHA) report. The report presents no basic geological data but brings up geological problems.

Q-80. Van Sambeek, L. L., Hansen, F. P., Gnirk, P. F., and Mahtab, A. A., 1978, "National Strategic Crude Oil Storage in the Weeks Island Dome Salt Mine: II. Rock Mechanics Evaluation," Amer. Assoc. Mech. Engr., 78-Pet-84.

This rock mechanics study was performed to assess the structural stability of old mine workings in relation to Morton Salt Company's proposed new deeper mine. Laboratory experiments were performed on the salt to determine strength and deformation characteristics. From these tests it was determined that a 300 ft (90 m) minimum thickness should be maintained between the old and new workings, but the possibility of blowouts has not been addressed in the study.

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